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NEUTRON TRANSMISSION VERSUS THICKNESS FOR SOME COMMON MATERIALS

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Department of the Army Project No. 512-10-001

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

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FJAllen/ATFutterer/WPWright/ic
Aberdeen Proving Ground, Md.
September 1962

NEUTRON TRANSMISSION VERSUS THICKNESS FOR SOME COMMON MATERIALS

ABSTRACT

Curves of neutron dose transmission versus thickness are presented for laterally infinite slabs of several common materials for neutrons incident at several fixed energies and angles. The materials are: water, polyethylene (borated), iron, concrete, Nevada Test Site soil (area 7, dry and 100 percent saturated), laminated slabs containing one inch of iron on the outside, a variable thickness of iron on the inside, and 3,6,9, or 12 inches of polyethylene sandwiched between the layers of iron. The neutron source energies are 0.5, 1, 2, 3, 5, and 14 MEV; the incident angles are 0°, 30°, 45°, and 70°.

Sufficient additional material is presented for interpretation, evaluation, and use of the results given.

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INTRODUCTION

During the past two years the Ballistic Research Laboratories have made detailed and extensive calculations of the transport of neutrons through several common materials. Some of the results of these calculations along with a description of the methods employed have been reported in References 1 - 4. The purpose of the present report is to present all of our calculated dose transmission factors for the materials treated. In some instances previous results have been improved; in these instances the present results supersede the previous results.

RESULTS AND DISCUSSION

Table 1 gives the densities and elemental compositions for all of the materials treated. The results are contained in Figures 1 - 44.

Differential elastic cross sections are used for oxygen and iron. For all other elements, elastic collisions are assumed isotropic in the center of mass system.

Inelastic collisons are handled in two ways. For each element a "threshold energy," E_{th}, is defined. For neutron energies (before any given collision) above E_{th}, a nuclear temperature model with the temperature, T, given by

$$T = K \sqrt{E}$$

is utilized. (T and E are measured in MEV.) For neutron energies before collison below E_{th}, a single level, E_{γ}, is assumed responsible for the inelastic scattering. All inelastic collisons are assumed isotropic in the center of mass system. Table 1 gives the values employed for E_{th}, E_{γ}, and K for the various elements of concern.

The rad is the unit of dose employed in the calculations. The flux to dose conversion factors are taken from Reference 5.

A cutoff energy of 10 electron volts is used throughout the calculations.

Figures 1 - 6 show the calculated dose transmission factors versus thickness for water for six source energies and four incident angles. Figures 7 - 12 give similar results for borated polyethylene, while Figures 13 - 18 give similar results for iron. Several machine calculations performed for

pure polyethylene slabs (up to six inches in thickness) show that the differences in dose transmission between pure polyethylene and borated polyethylene are negligible.

Figures 19 - 24 represent an attempt to scale neutron transport results for several hydrogenous materials having quite different hydrogen contents. The results are moderately good: a scale factor is found for each material for each source energy but it is not always possible to draw a single curve through the data for each incident energy, angle, and all materials. In some cases two curves are required. One curve suffices for water and polyethylene; the other suffices for Nevada Test Site soil (dry and 100 percent saturated) and for concrete. The composition for Nevada Test Site soil is based on Reference 6; that for concrete is based on Reference 7. For these materials, atoms of all elements other than hydrogen, oxygen, aluminum, or silicon were replaced by silicon atoms. (This changes the density slightly.)

Soils and concretes vary greatly in composition; their hydrogen contents also vary greatly. Often the compositions are not well known; in the case of soils the compositions often vary widely over small distances while their hydrogen contents vary with the weather. Therefore, in many instances, high accuracy is not required; the curves in Figures 19 - 24 can then be used to estimate neutron transmission through soil or concrete satisfactorily.

Figures 25 - 42 give the dose transmission factors for laminated slabs of iron and borated polyethylene. These slabs contain one inch of iron on the outside, a variable thickness of iron on the inside and 3, 6, 9, or 12 inches of polyethylene sandwiched between the layers of iron. The curves have not been drawn for values of the abscissa corresponding to less than one inch of iron. In this region all of the iron is on the outside, while values of the abscissa greater than unity imply one inch of iron on the outside and the remainder on the inside. Thus the curves should be cusped at an abscissa of unity. Since the calculated results do not suffice to determine the detailed shapes of the curves, the curves have not been drawn for values of the abscissa less than unity.

Figures 43 and 44 give dose transmission factors for normally incident neutrons for five source energies for slabs of water and borated polyethylene. The slab thicknesses here are greater than those in Figures 1 - 12. In the

vicinity of twelve inches, the results in Figures 43 and 44 differ slightly from those in Figures 1 - 12. This is because additional Monte Carlo calculations were made to obtain the results contained in Figures 43 and 44. These were averaged with previous results for thicknesses at which previous results were available. Therefore, the results in Figures 43 and 44 have slightly smaller statistical errors associated with them than the previously given results.

FURTHER DISCUSSION

Most of the results were obtained by Monte Carlo calculations. A description of the basic machine program is contained in Reference 1. This program has been modified in two important respects since the publication of Reference 1. A "splitting" technique has been incorporated in the program. This allows the calculation of much deeper penetrations than had been possible previously. Handling of the information generated on the slab interior has been changed. In particular, this allows making calculations for several slab configurations simultaneously. (It also gives rise to more useful information on the slab interior than that described in Reference 1, but that is not of concern here.)

Reference 3 describes a method of calculating deep penetrations based on the fact that (the scattered) neutrons penetrating a thick medium achieve a quasi-equilibrium several mean free paths from the source. This method, in effect, allows determination of a relaxation length for the scattered neutrons once quasi-equilibrium is established. Then the transmission for any thickness is readily calculated; however, the accuracy diminishes as the thickness increases and there is no way of knowing at what depth the results cease to be reliable. This method had been used for calculations of neutron transmission through slabs several inches thicker than calculable by analog Monte Carlo prior to the incorporation of the splitting technique in the basic machine program.

Calculations made with the aid of the splitting technique have served to substantiate the validity of the quasi-equilibrium method described in Reference 3. In addition, the availability of calculated results for deeper penetrations than could be made without the splitting technique has allowed more accurate determination of the relaxation length applicable after quasi-equilibrium is achieved. The deep penetration results also give good

information on the approach to quasi-equilibrium. This improved information has been used to calculate some of the results in this report, while other of the deep penetration results have been made with the splitting technique. It has not been possible to calculate all of the results employing the splitting technique since computing machine time becomes very long for the deep penetrations. However, a good many of the calculations were made by this method on occasional weekends when the ORDVAC would otherwise have been idle. The quasi-equilibrium method has been checked against the splitting results whenever the latter were available since calculations by the quasi-equilibrium method can be performed rapidly by hand. With the improved values of the relaxation lengths now available, the two calculations agree quite well in all cases.

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William P. Wright
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APPENDIX

THE DEEP PENETRATION PROBLEM

One of the outstanding problems in radiation transport is the calculation of the transmission through a medium many mean free paths thick. The problem is more difficult for laminated slabs than for a homogeneous material and it is more difficult for oblique than for normal incidence. Recently a splitting technique* was incorporated into the BRL Monte Carlo neutron transport code to deal with this problem. It is of some interest to consider what advantage is gained by this technique.

We define the splitting advantage to be the ratio of the computing time required to obtain a result by analog Monte Carlo to the time required to obtain a result of like statistical validity with the aid of the splitting technique. Figure A-1 gives three curves of splitting advantage versus probability of transmission. One is a theoretical curve based on the study in Reference 8. The other two are based on machine runs made with three splitting surfaces and seven splitting surfaces, respectively.**

It may be seen that the three curves have the same shapes. Seven splitting surfaces are much better than three. Use of more surfaces would bring about a further improvement. The theoretical curve is based on a simple case amenable to analytical treatment: only absorption and forward scattering are allowed. In obtaining the theoretical curve no allowance was made for any machine operations other than those required to treat collisions. The points on the two lower curves in Figure A-1 are based on machine runs for several materials (including some laminated slabs), various thicknesses, incident energies and incident angles. It was not always possible to choose either the positions of

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* In this technique, a neutron, upon crossing any of several preselected surfaces, is split into several neutrons. The weight of each of these is reduced in proportion to the amount of splitting, so that the results are unbiased. The simulation of the neutron's physical interaction processes is not altered in this procedure.

** Three splitting surfaces were available in the machine program before seven (the maximum available); several calculations were made with three splitting surfaces. The reason for this is connected with the difficulties caused by the ORDVAC's small (4096 word) fast memory. Programming compromises had to be made in order to obtain accurate physical input along with the desired multiplicity of output information.

the splitting surfaces or the amount of splitting at each surface in an optimum manner. For the deep penetrations calculated, splitting factors larger than two were required at most of the surfaces since only seven splitting surfaces are available in the machine program. In view of these facts, it is perhaps surprising that the curve for 7 splitting surfaces in Figure A-1 is as close to the theoretical curve as it is.

The preceding discussion lends strong support to the following, intuitively clear, assertion: in calculating the probability of transmission, the advantage gained by splitting is mainly a function of this probability itself, and is almost independent of the detailed sequences of events, the totality of which determine this probability. This is in contrast to the state of affairs with importance sampling: for use of this technique, one must know which classes of event sequences are important beforehand in order to increase the sampling of those trajectories which make the chief contributions to the transmission.

Figure A-1 shows that the splitting advantage does not increase quite as rapidly as the probability of transmission decreases. For example, a decrease in probability of transmission from 10^{-2} to 10^{-7}, or five orders of magnitude, is accompanied by a gain in splitting advantage of but four orders of magnitude. This means that ten times as much time is required to compute the probability of transmission for the case of lesser liklihood. Thus, although the advantage gained by splitting is very great, it is not great enough to make possible the calculation of arbitrarily deep penetrations.

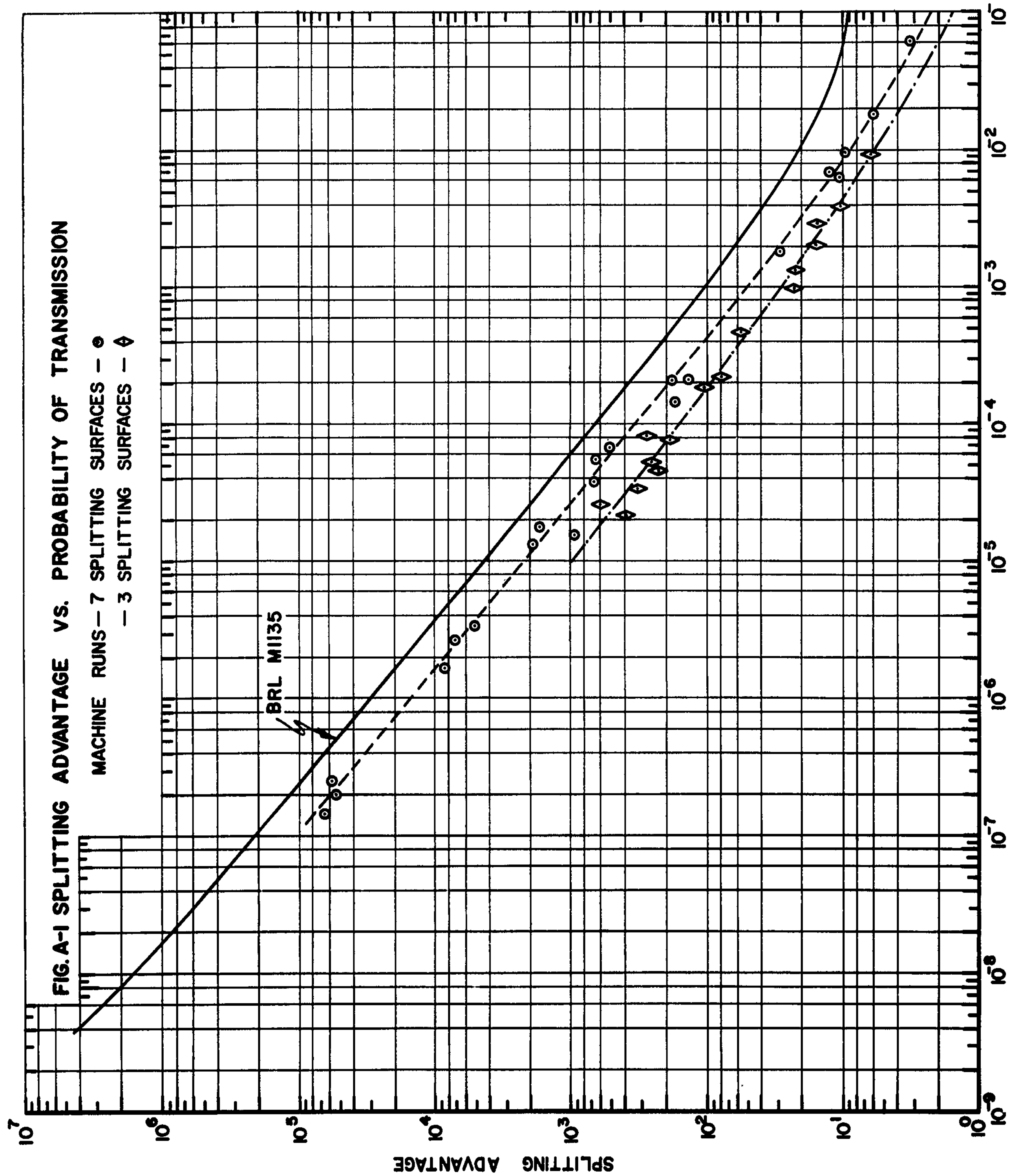


FIG. A-1 SPLITTING ADVANTAGE VS. PROBABILITY OF TRANSMISSION

TABLE 1

ELEMENTAL COMPOSITIONS AND AUXILIARY INFORMATION

Material	Density Grams/cm^3	Elements Contained	Atoms per cm^3 (10^{21})	E_{th} (MEV)	E_γ (MEV)	K (MEV$^{1/2}$)
Water	1.0	H	66.9	-	-	-
		O	33.45	10.0	6.3	0.469
8 percent Borated	.97	H	76.8	-	-	-
Polyethylene		C	39.2	10.0	4.43	0.267
		B^{10}	0.658	-	-	-
		B^{11}	2.67	-	-	-
Iron	7.88	Fe	84.9	3.0	0.85	0.267
Nevada Test	1.15	H	8.553	-	-	-
Site Soil (Area 7)		O	22.68	10.0	6.3	0.469
Dry		Al	2.014	3.0	0.96	0.294
		Si	9.533	6.0	1.8	0.294
Nevada Test Site (Area 7) 100 percent	1.25	H	16.87	-	-	-
Saturated		O	27.0	10.0	6.3	0.469
		Al	1.976	3.0	0.96	0.294
		Si	8.963	6.0	1.8	0.294
Concrete	2.26	H	13.75	-	-	-
		O	45.87	10.0	6.3	0.469
		Al	1.743	3.0	0.96	0.294
		Si	20.15	6.0	1.8	0.294

FIG. 1 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENT

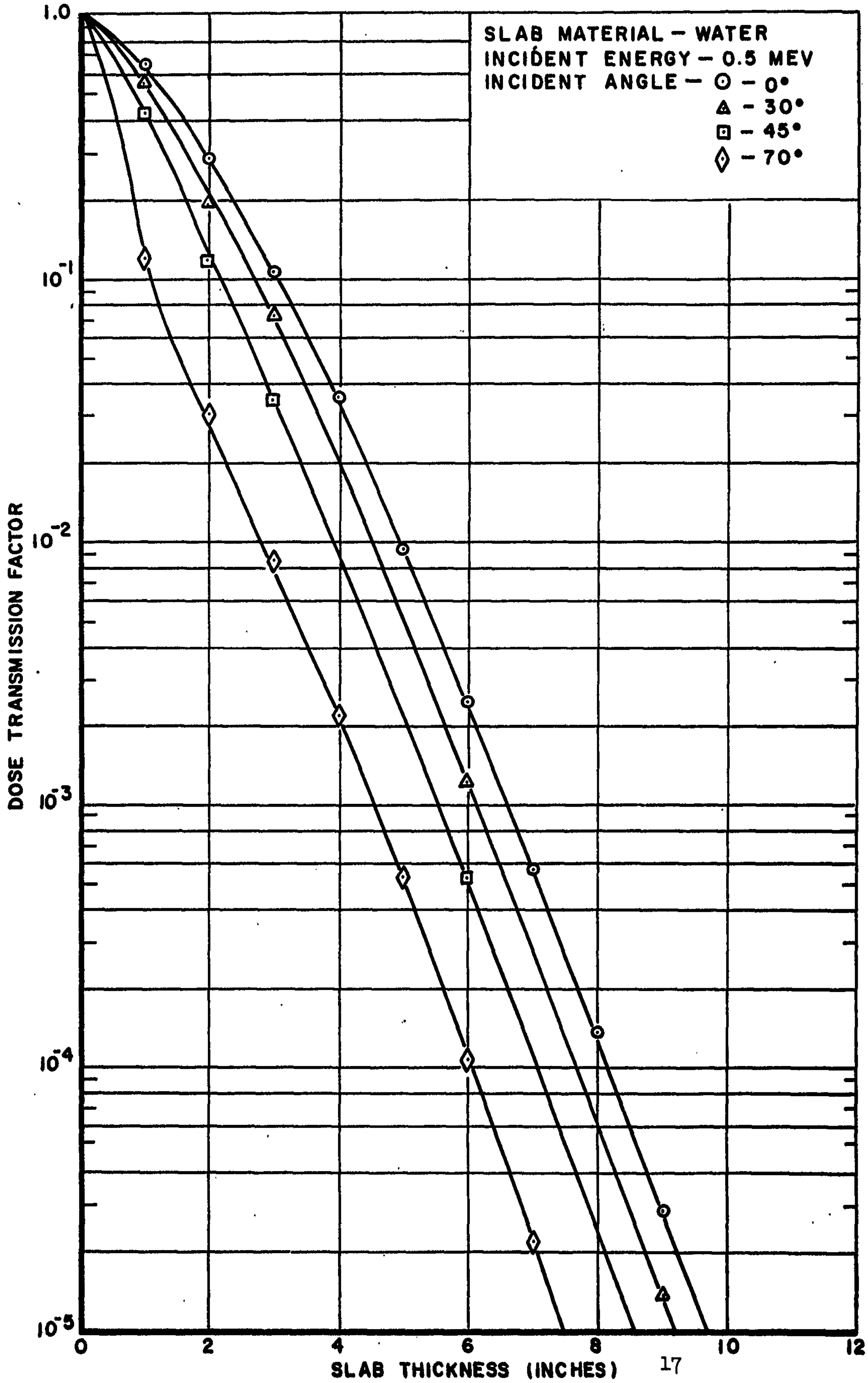


FIG. I (cont'd) NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

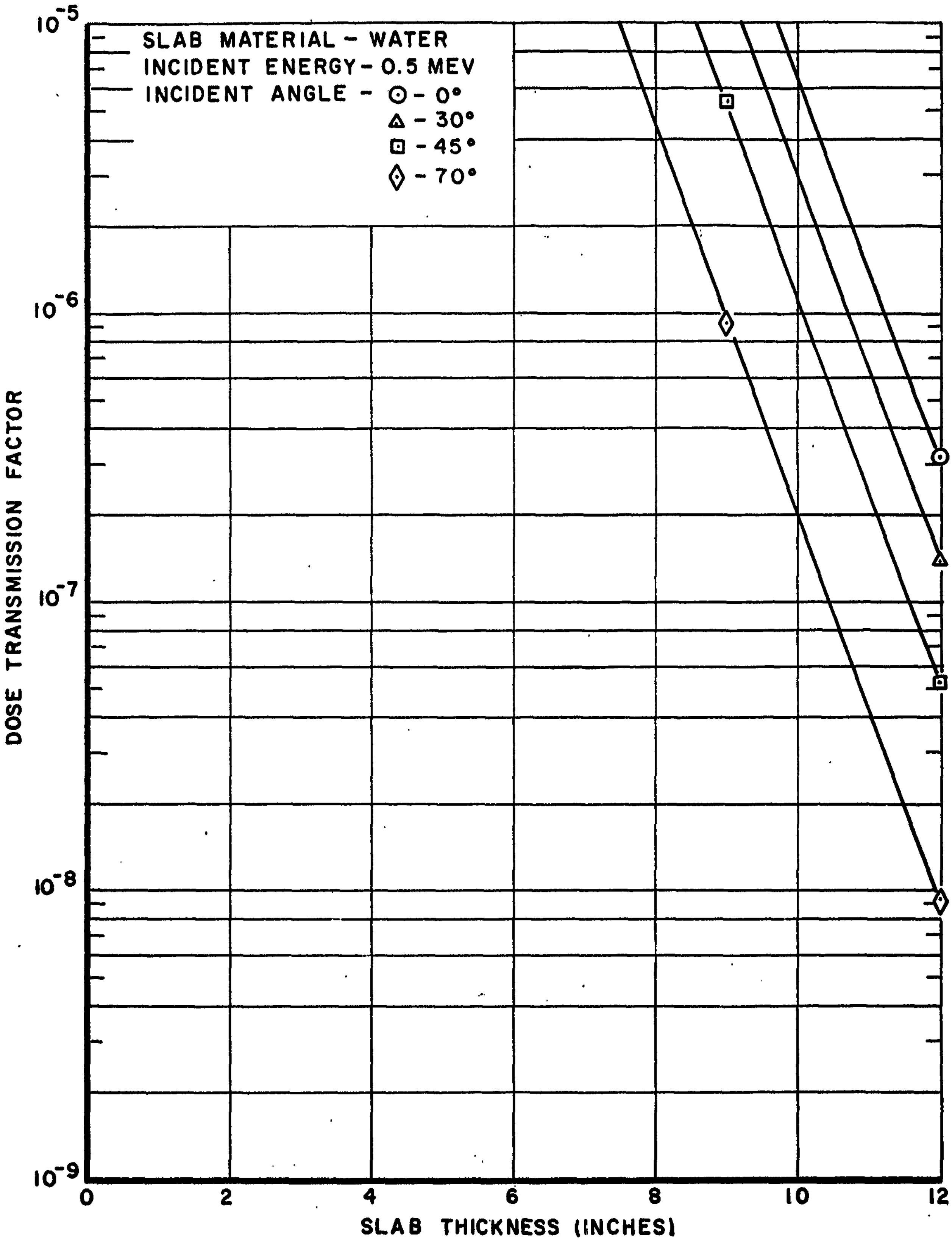


FIG. 2 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

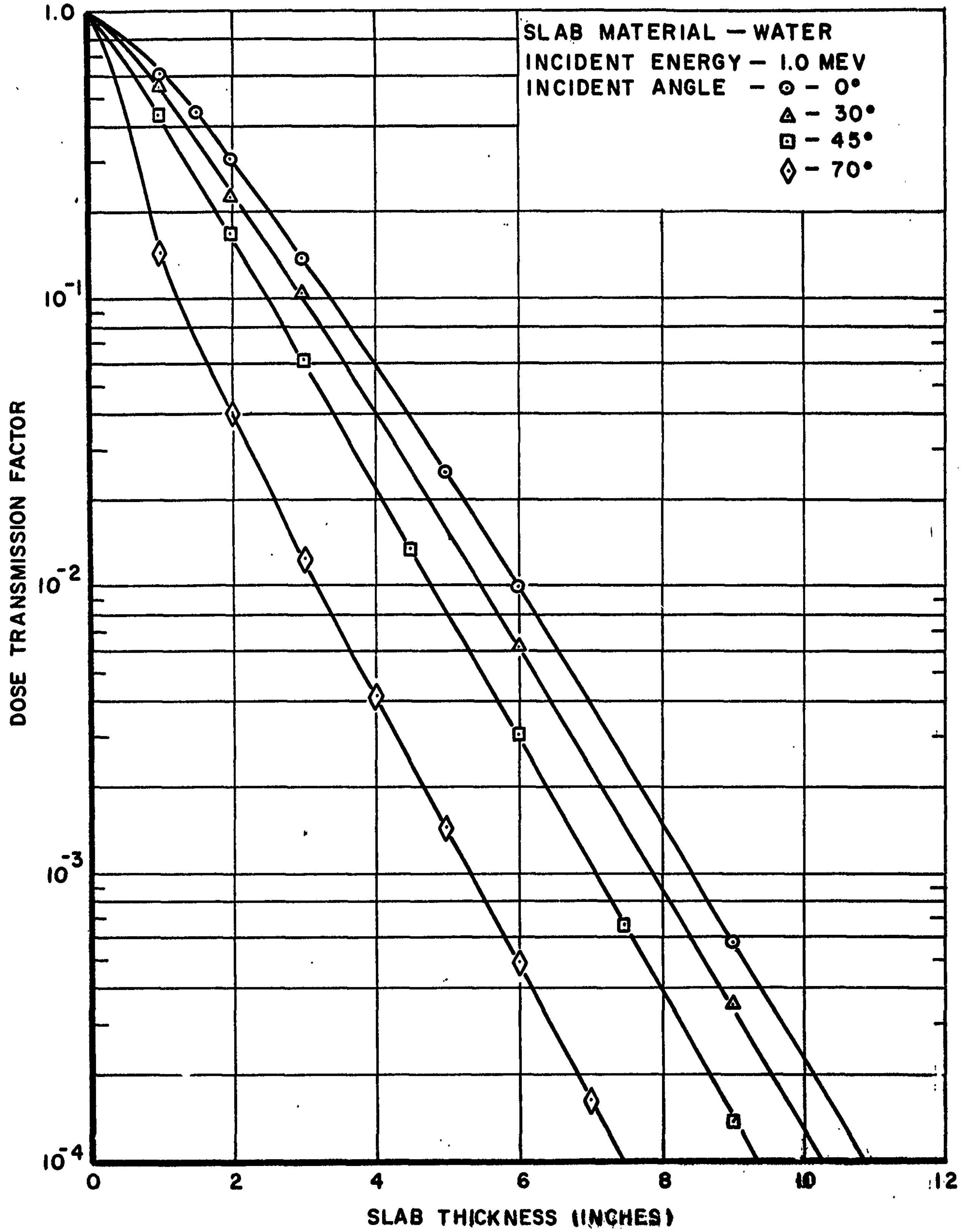


FIG. 2 (cont'd) NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

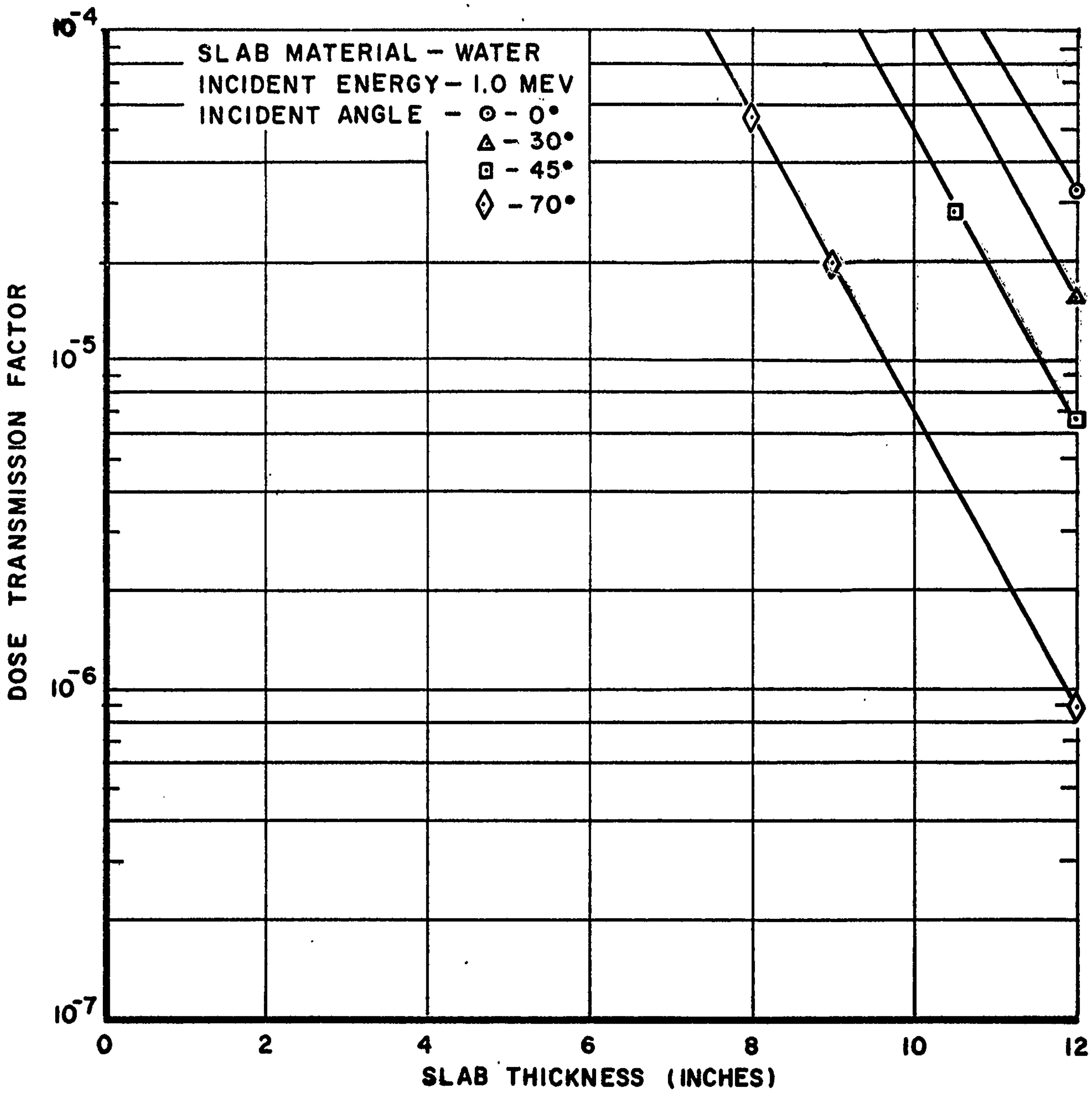


FIG. 3 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

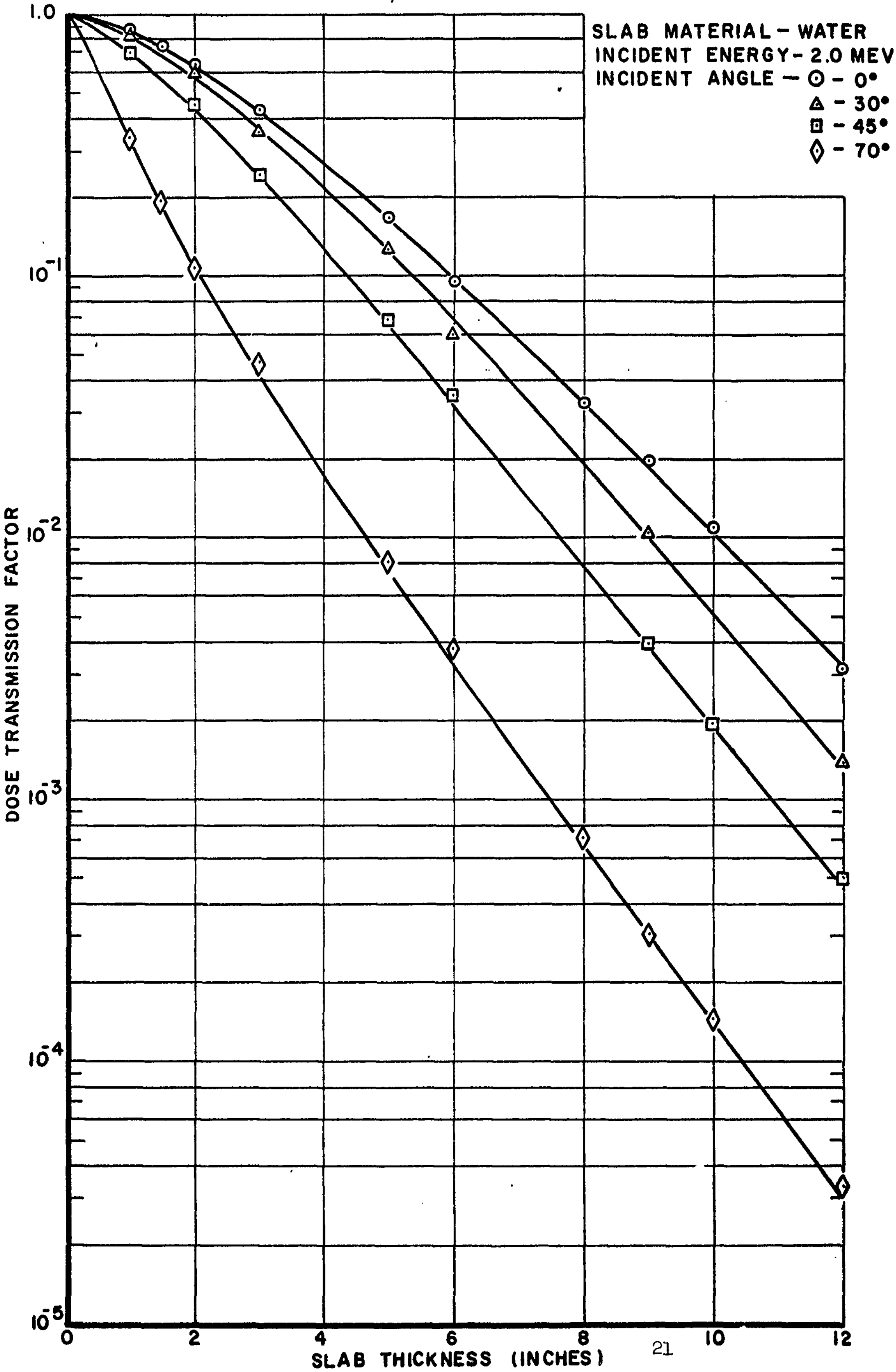


FIG. 4 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

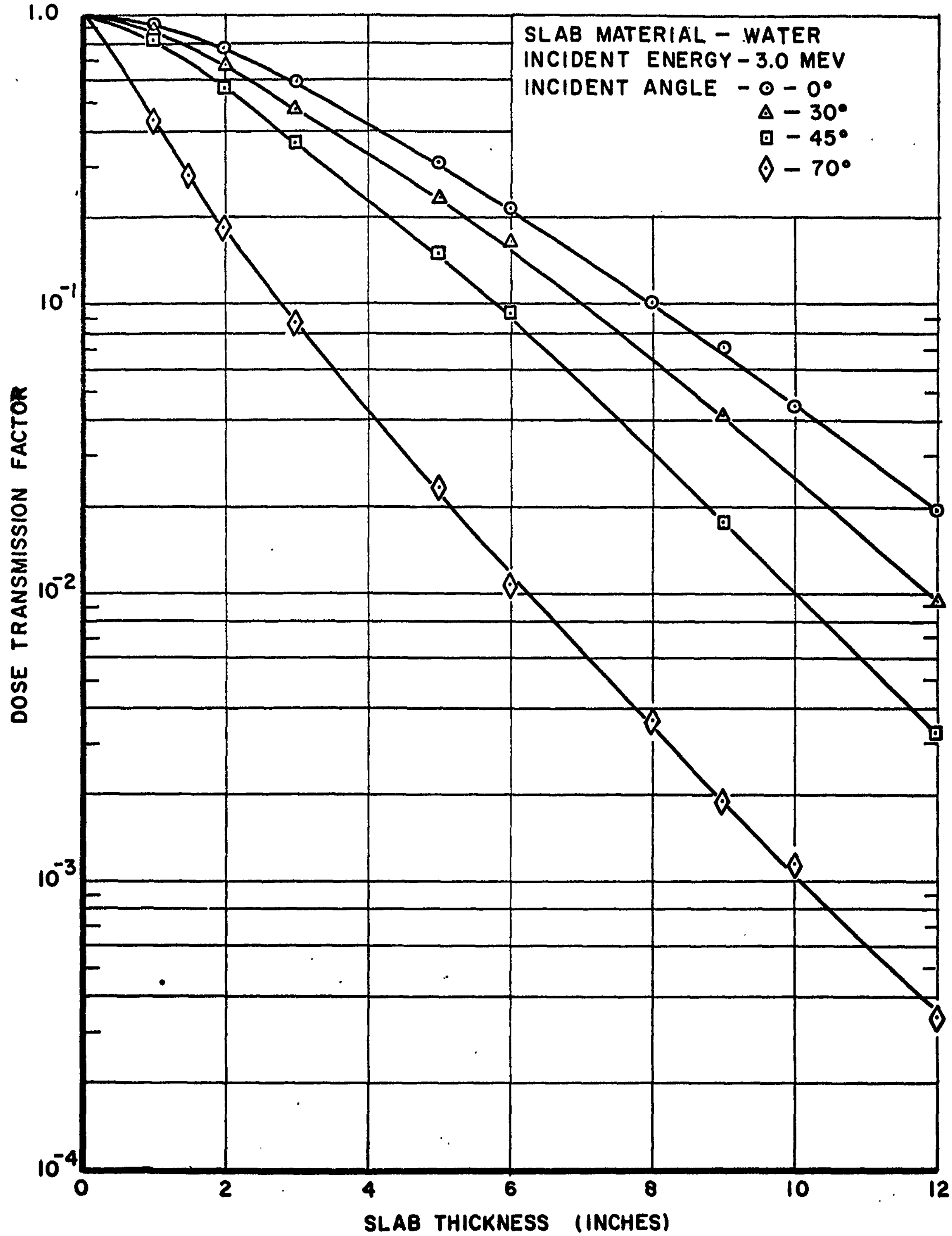


FIG. 5 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

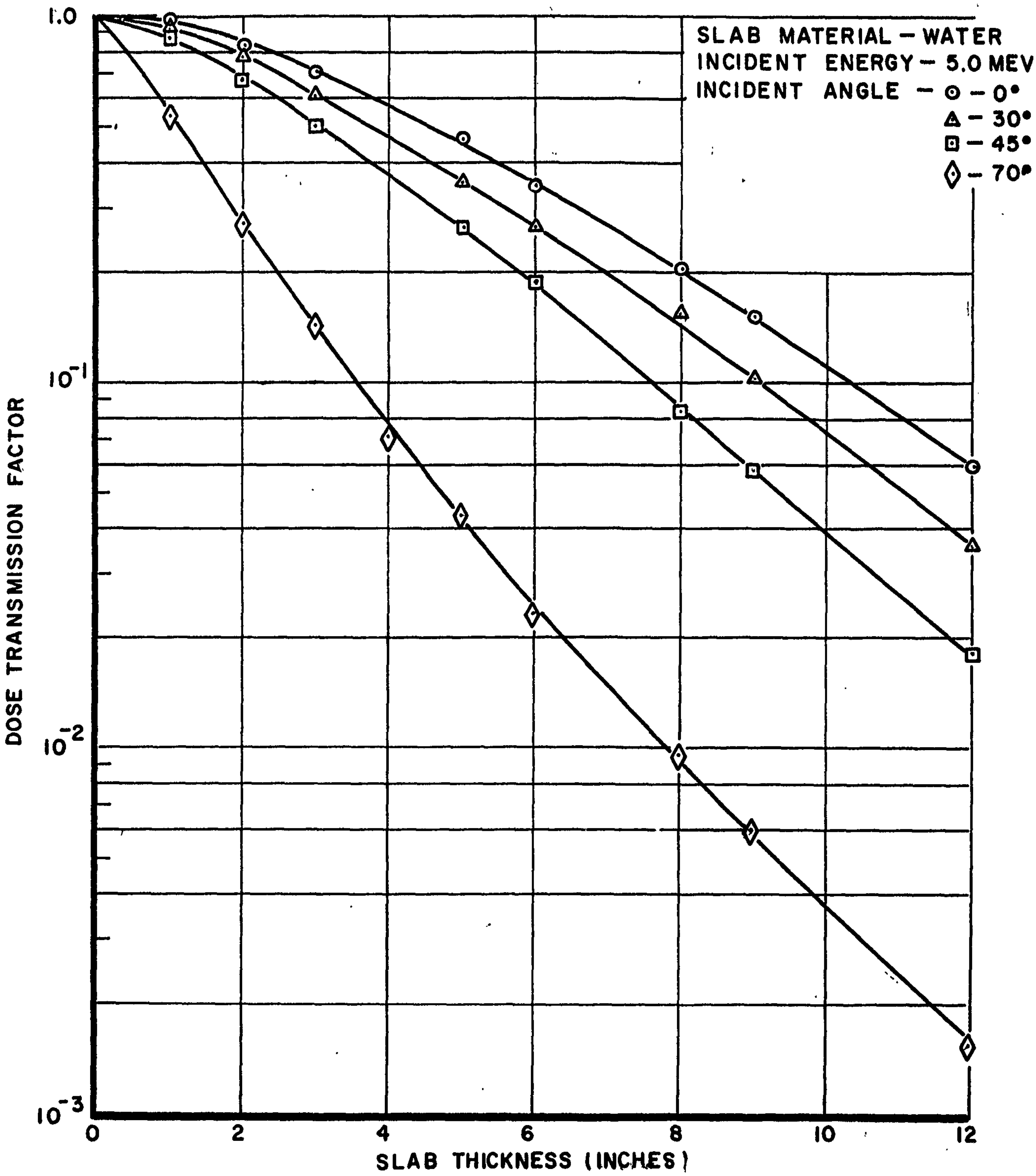


FIG. 6 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

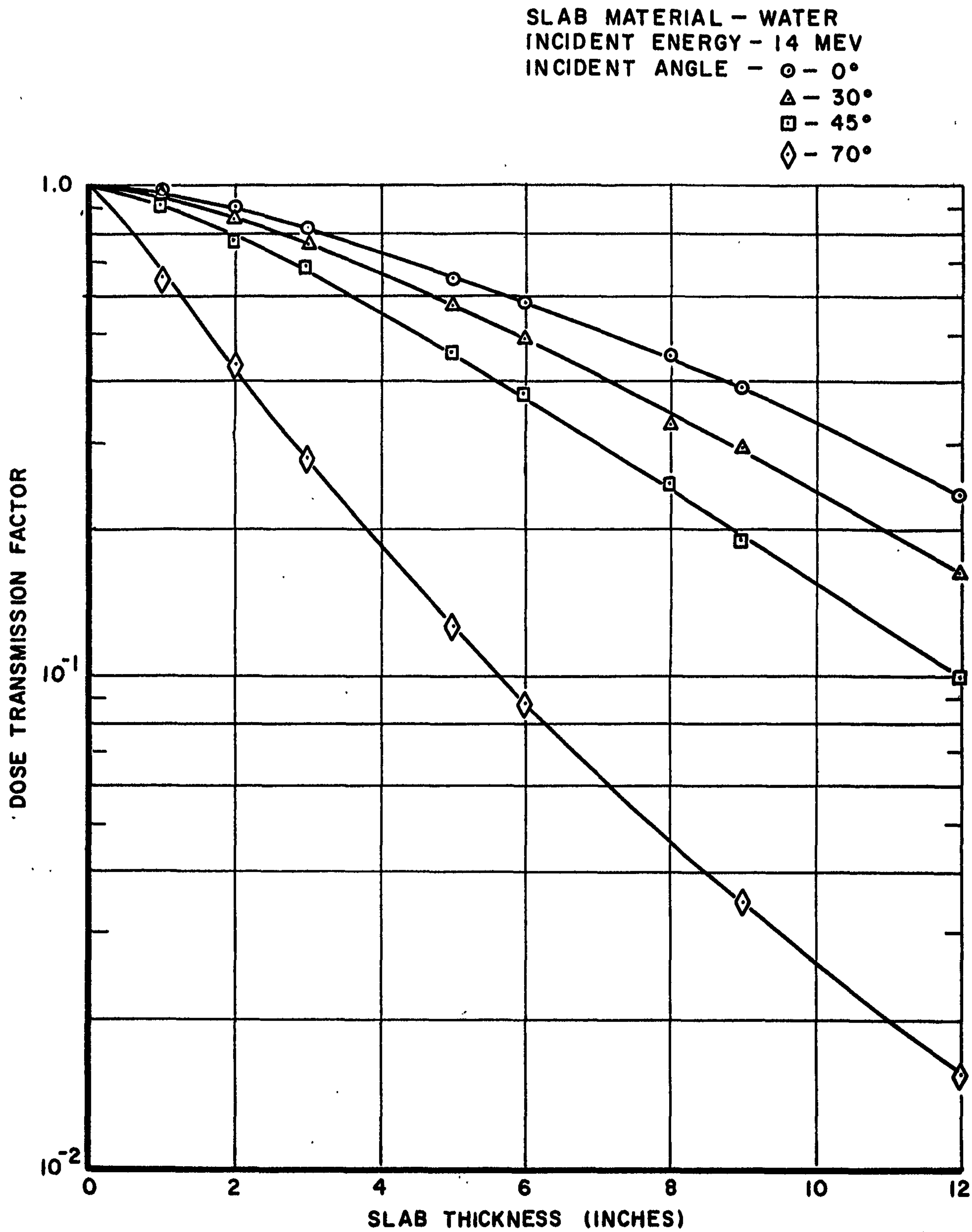


FIG. 7 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

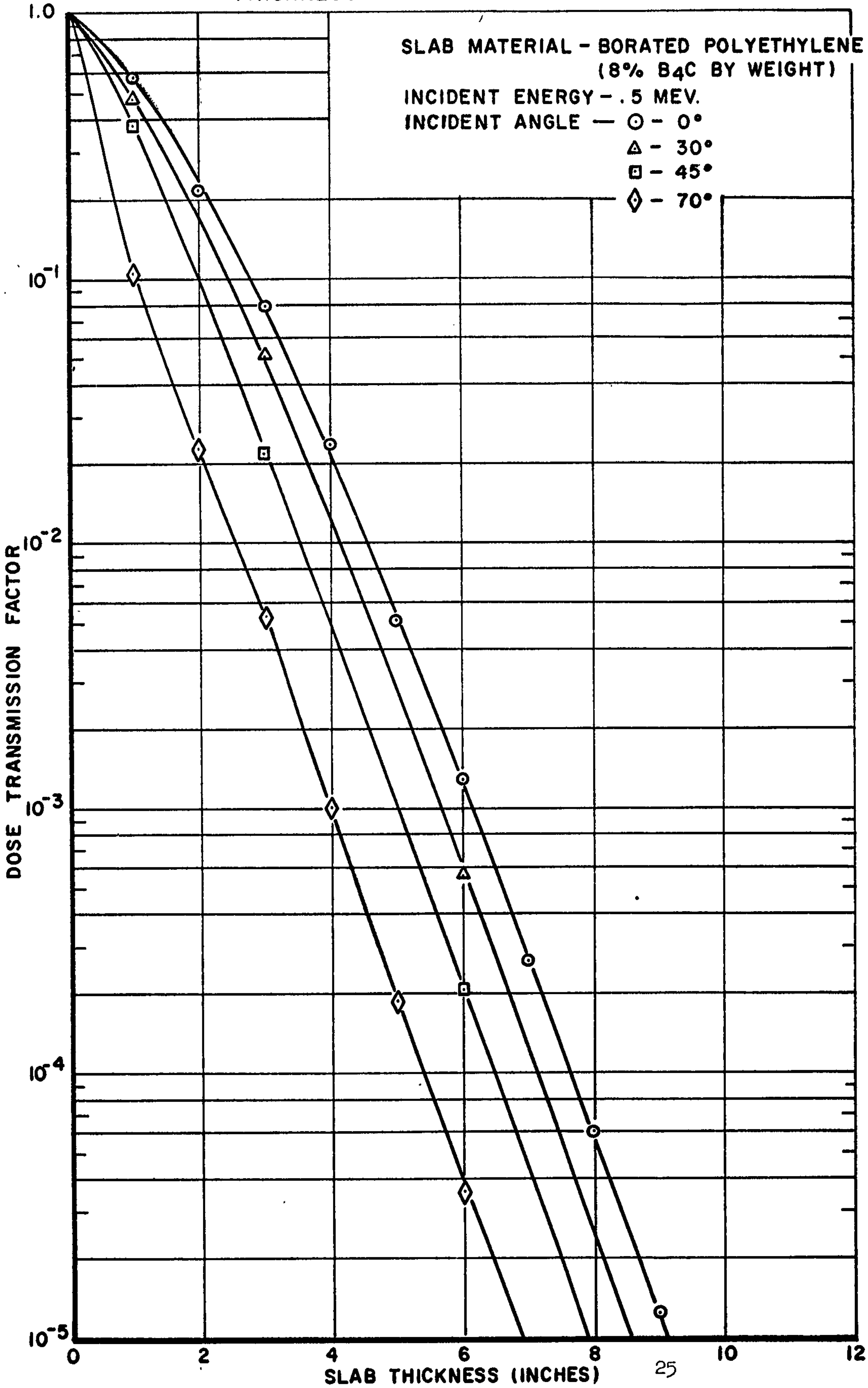


FIG. 7 (cont'd) NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

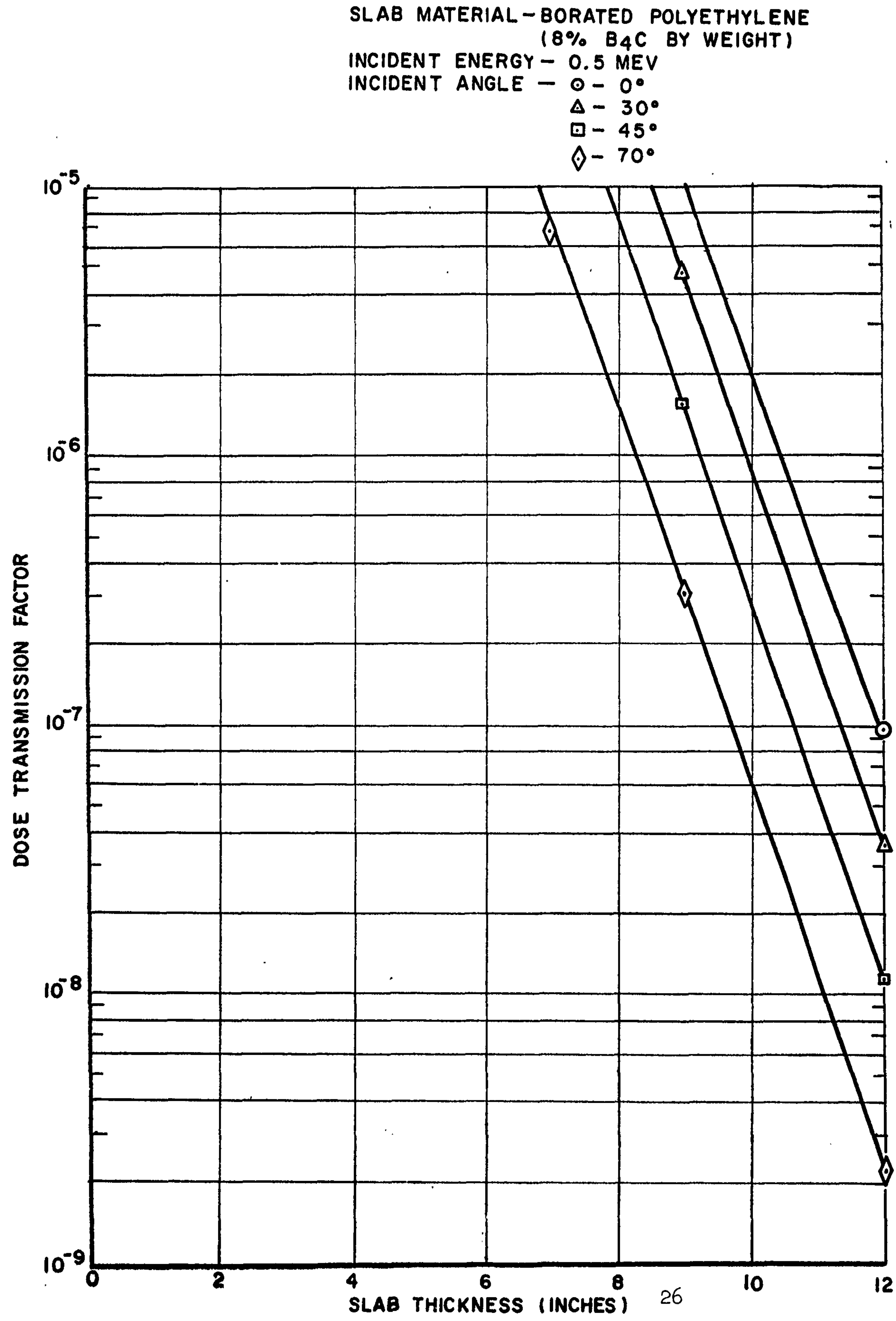
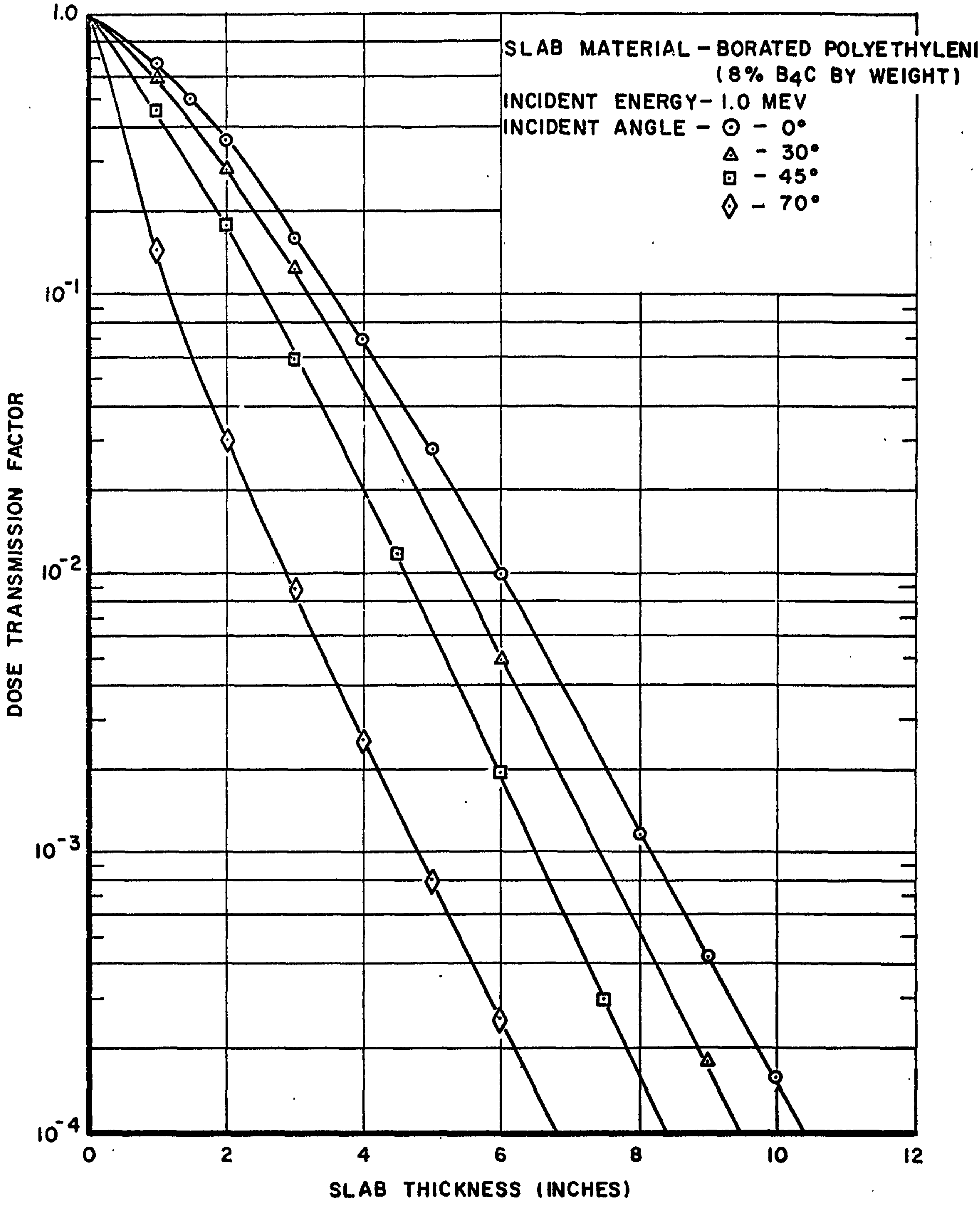


FIG. 8 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE



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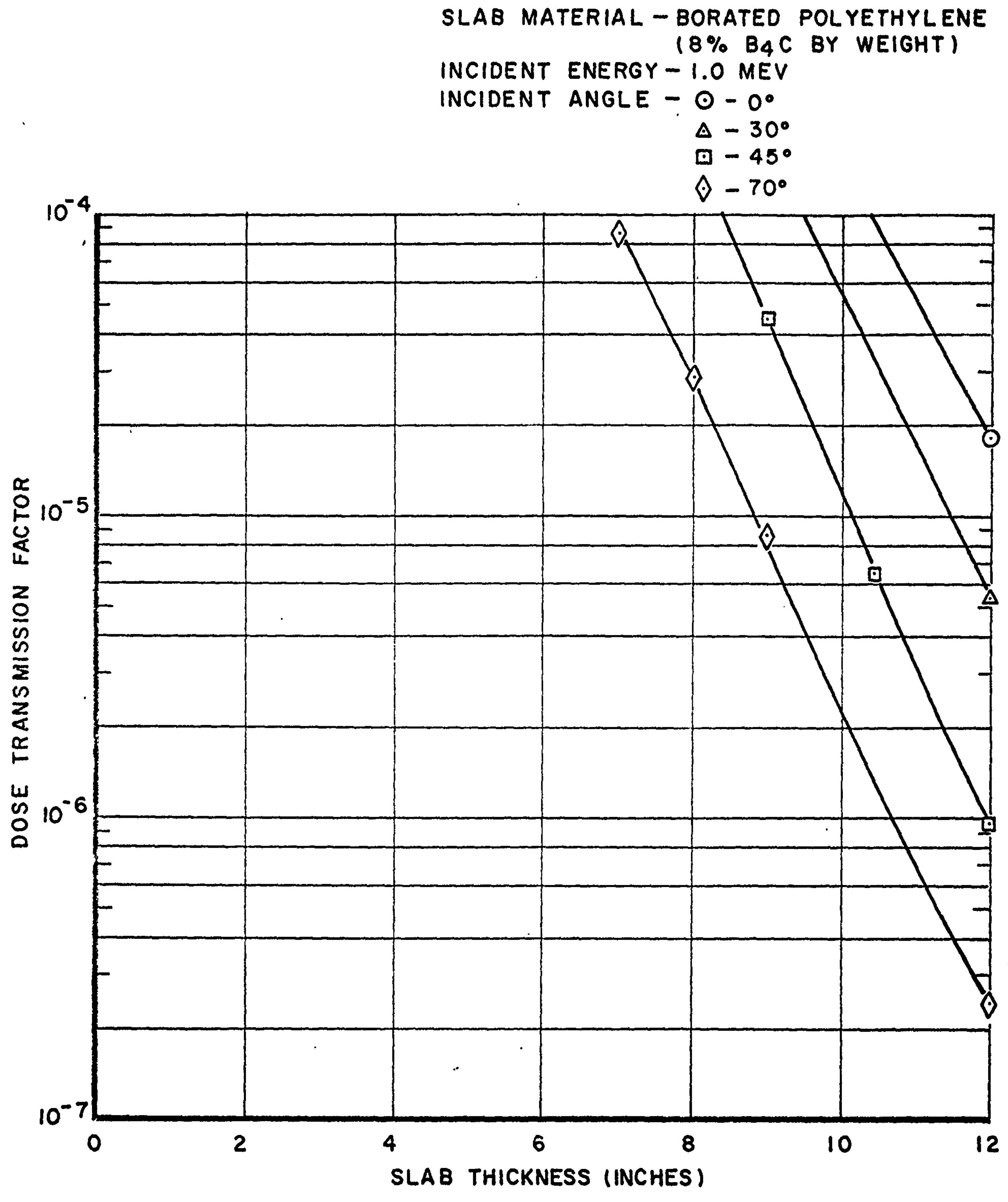


FIG. 9 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

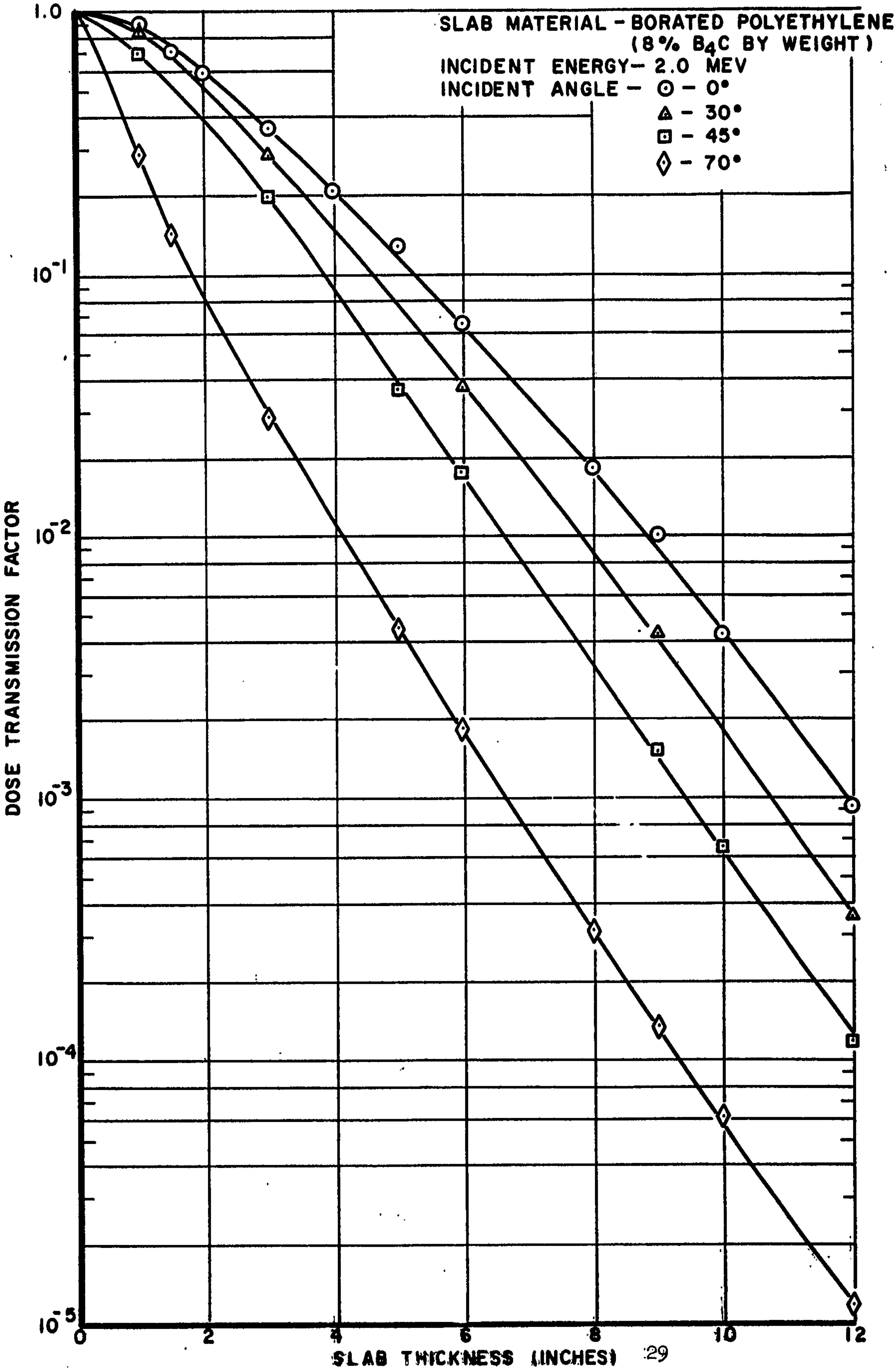


FIG. 10 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

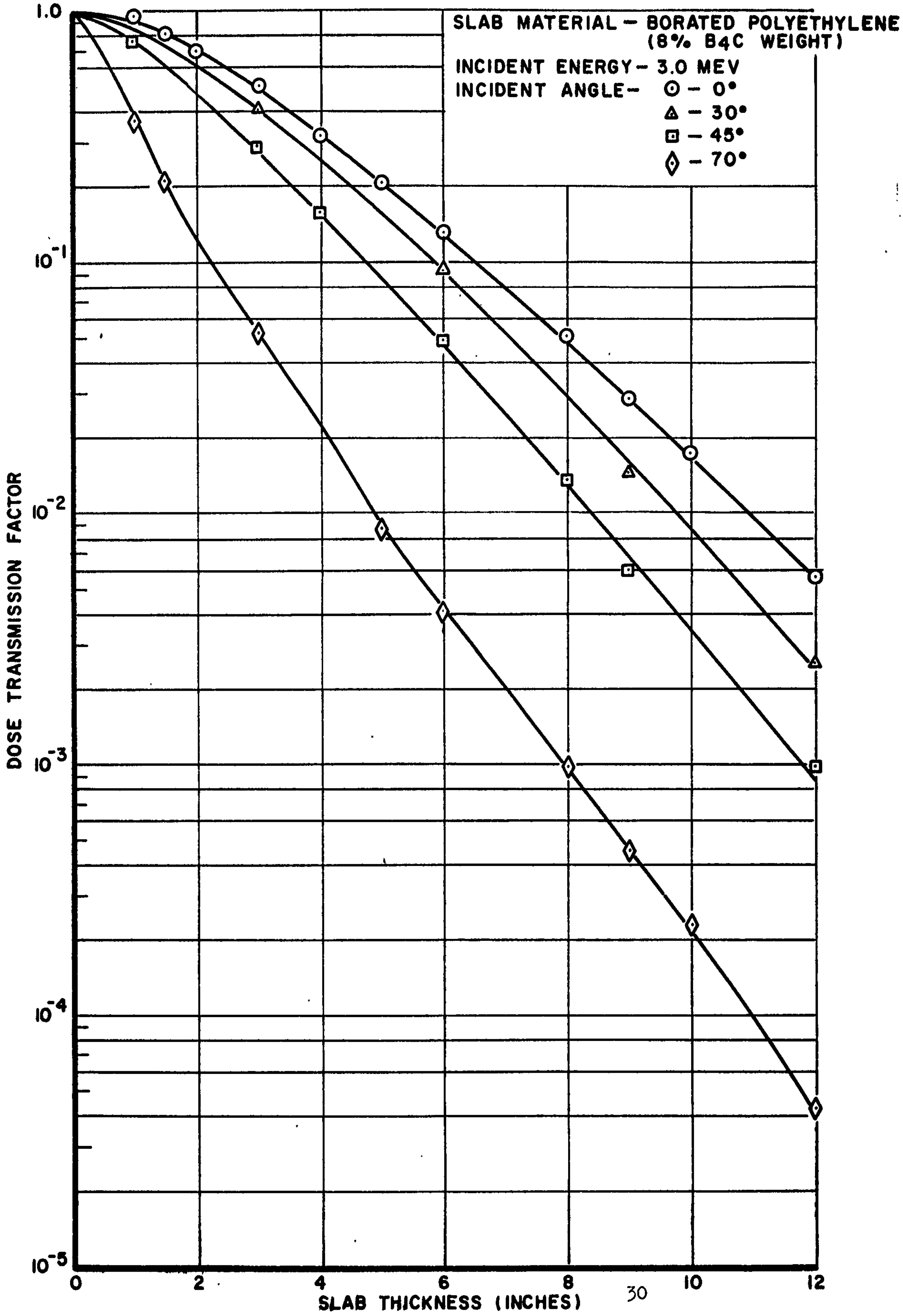


FIG. 11 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

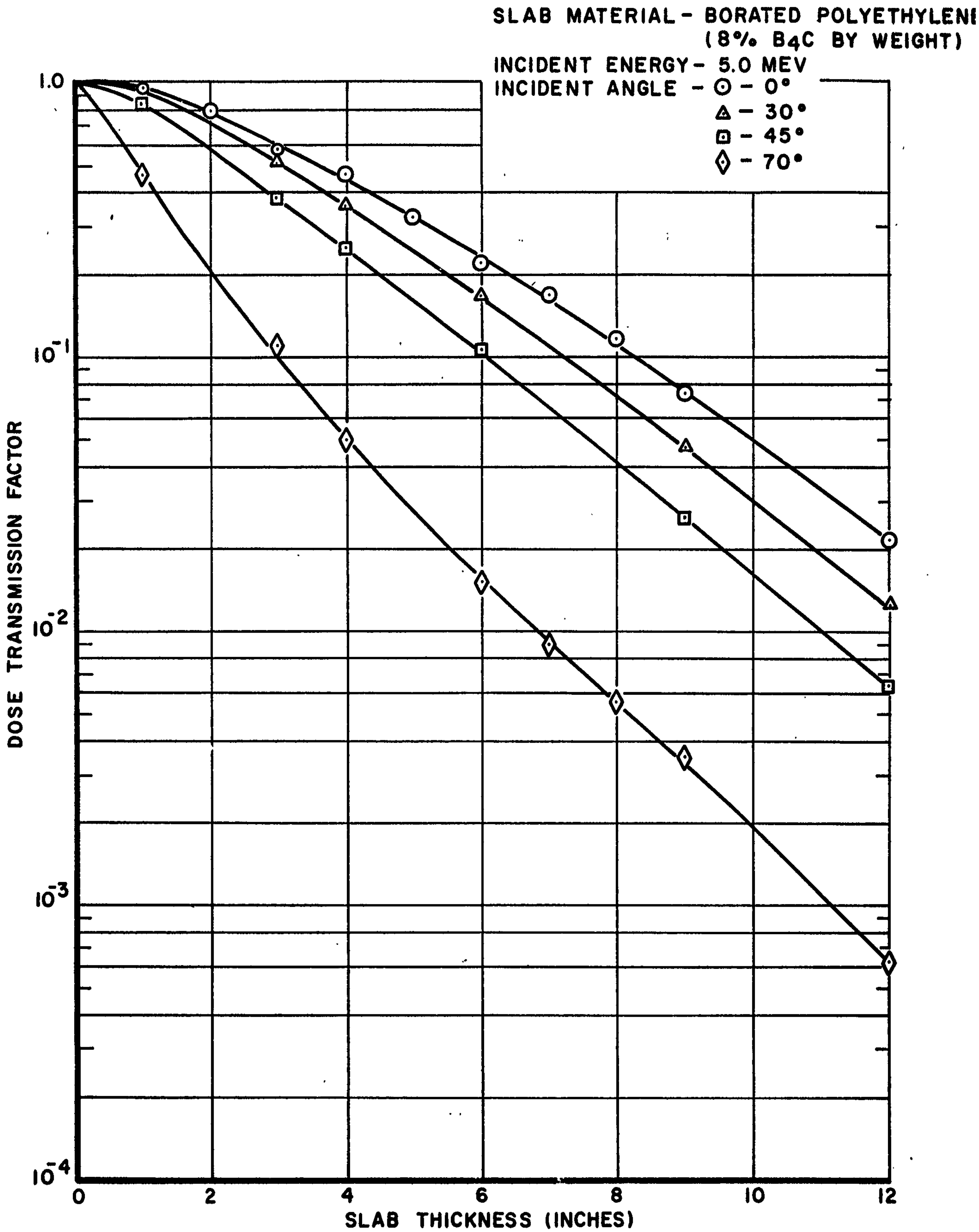
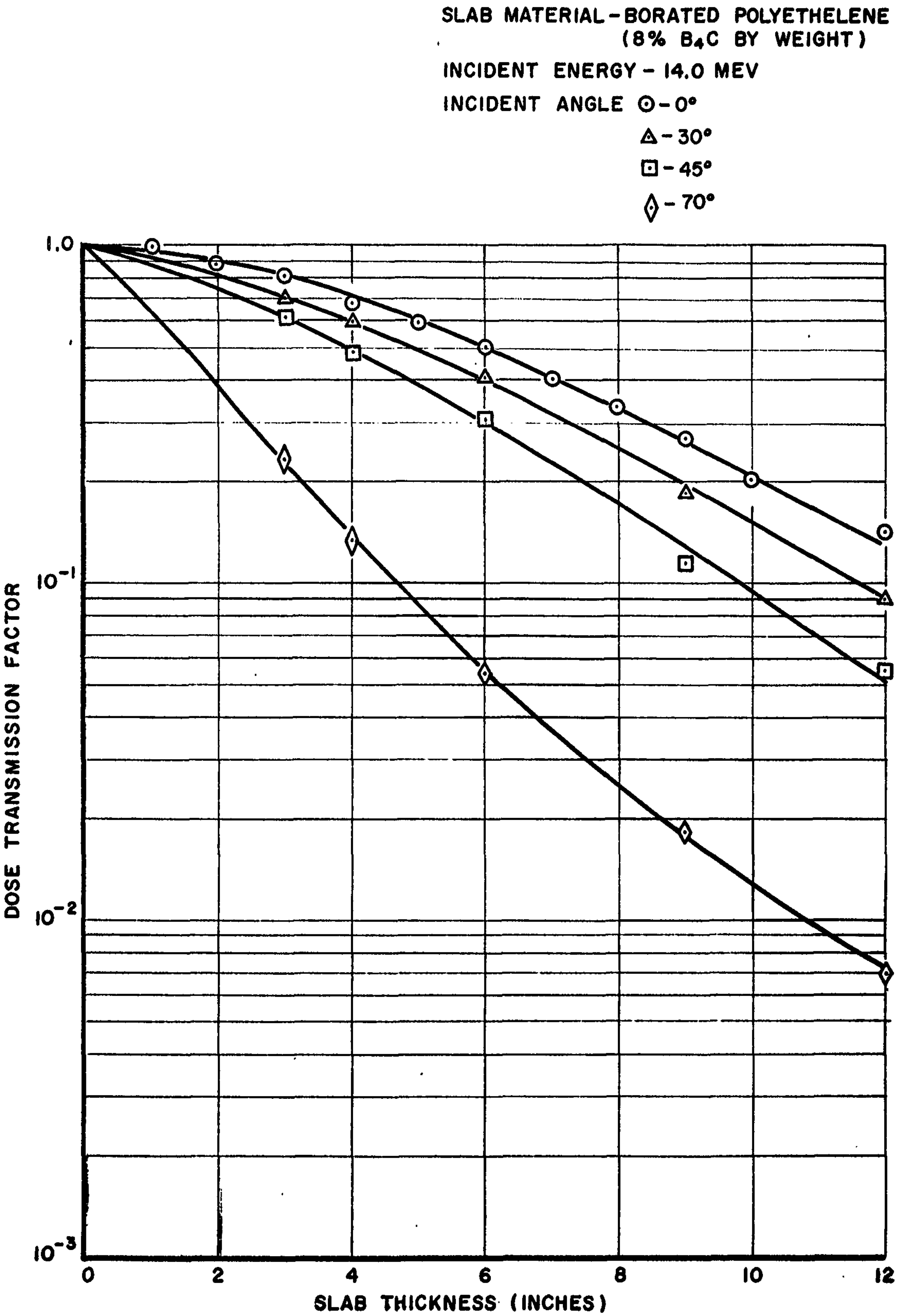


FIG. 12 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE



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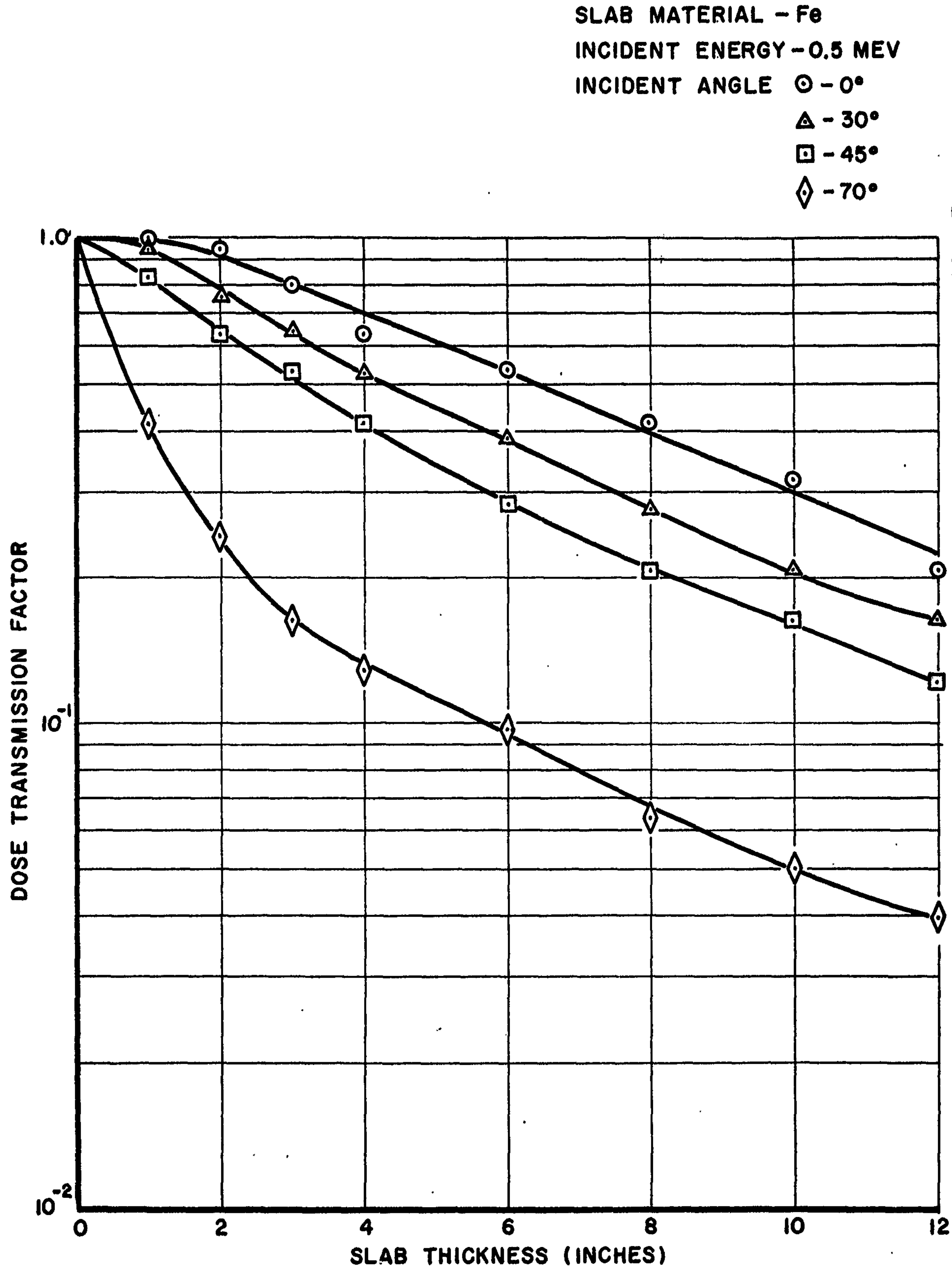

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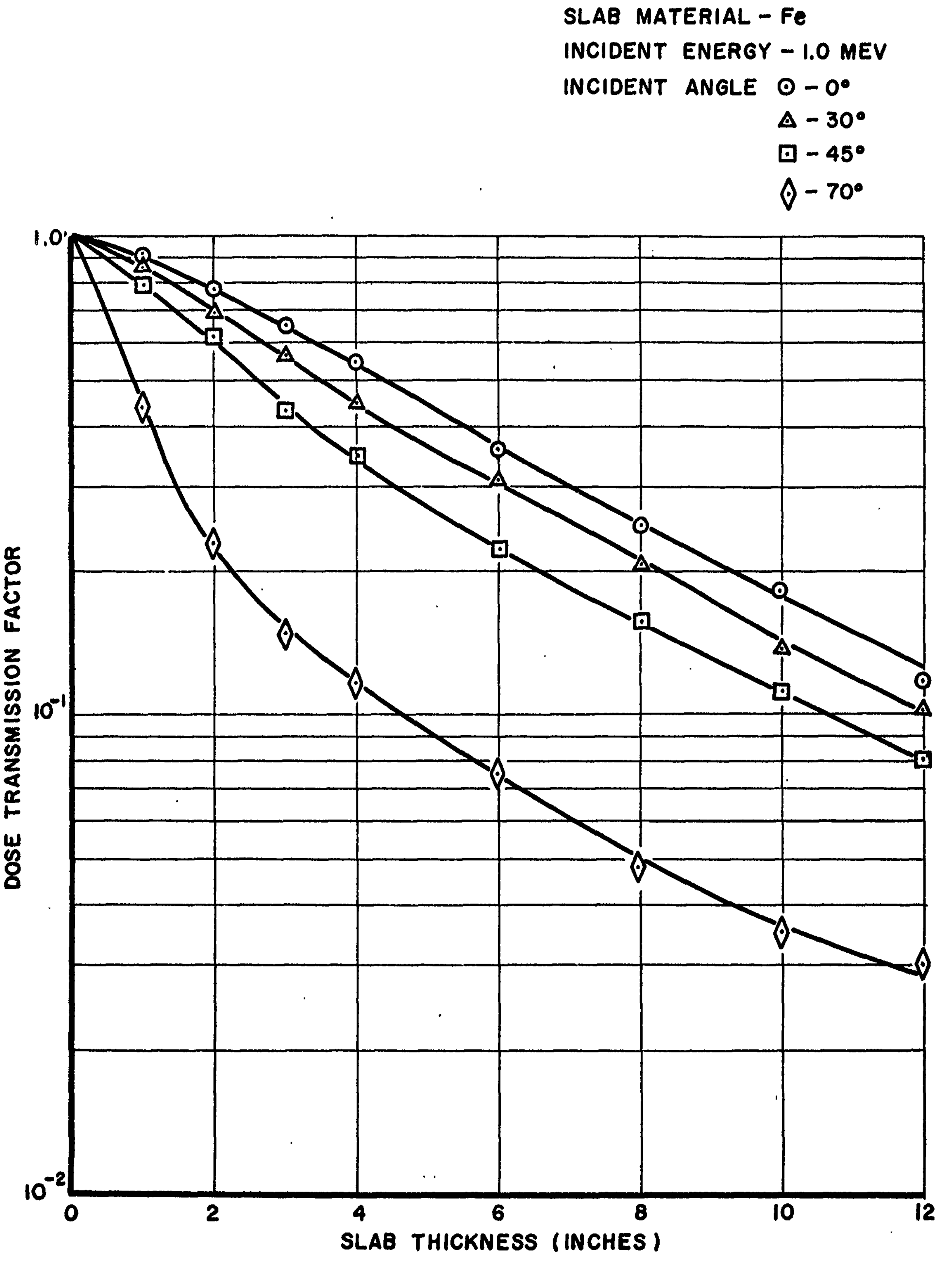

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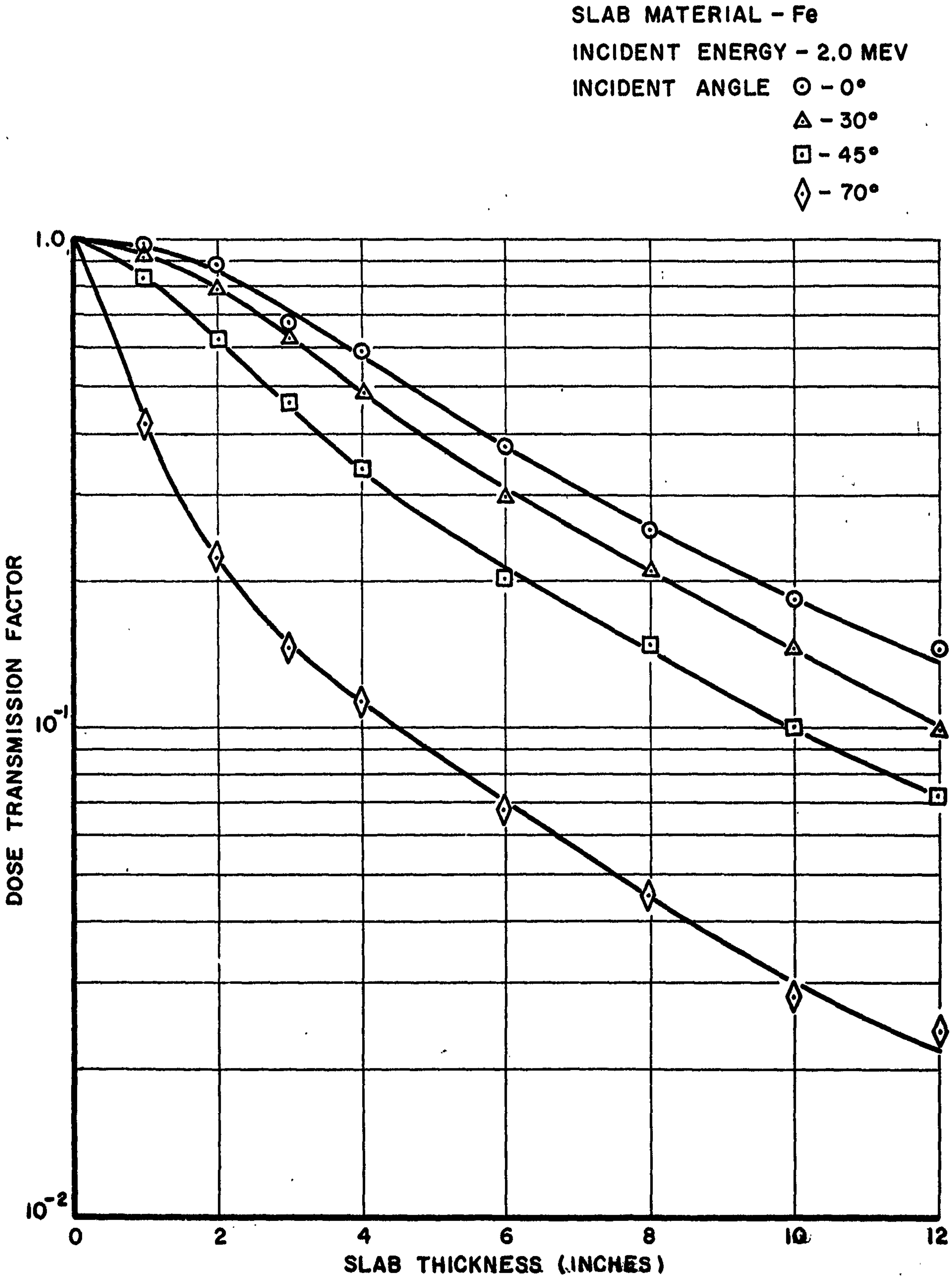

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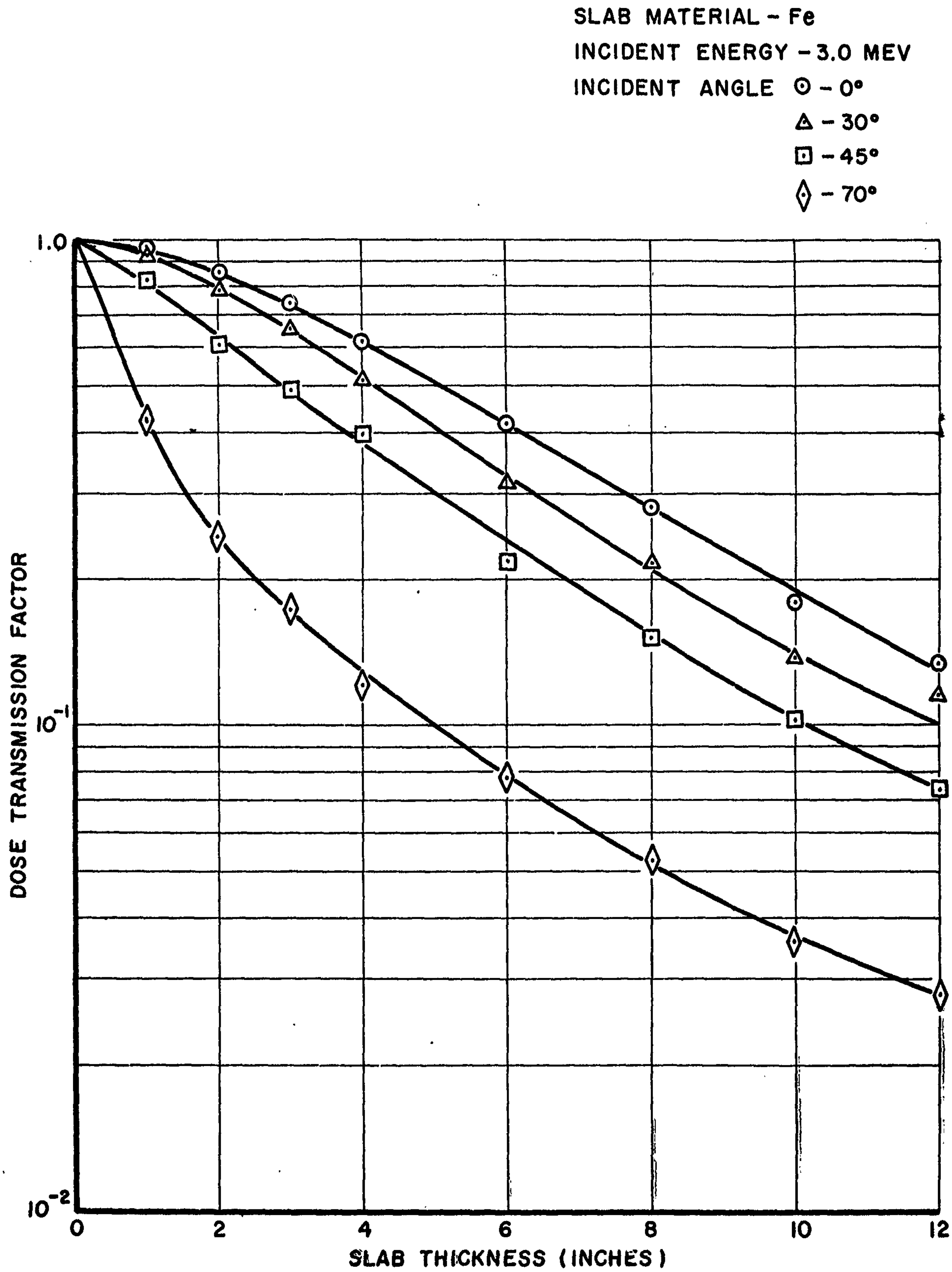
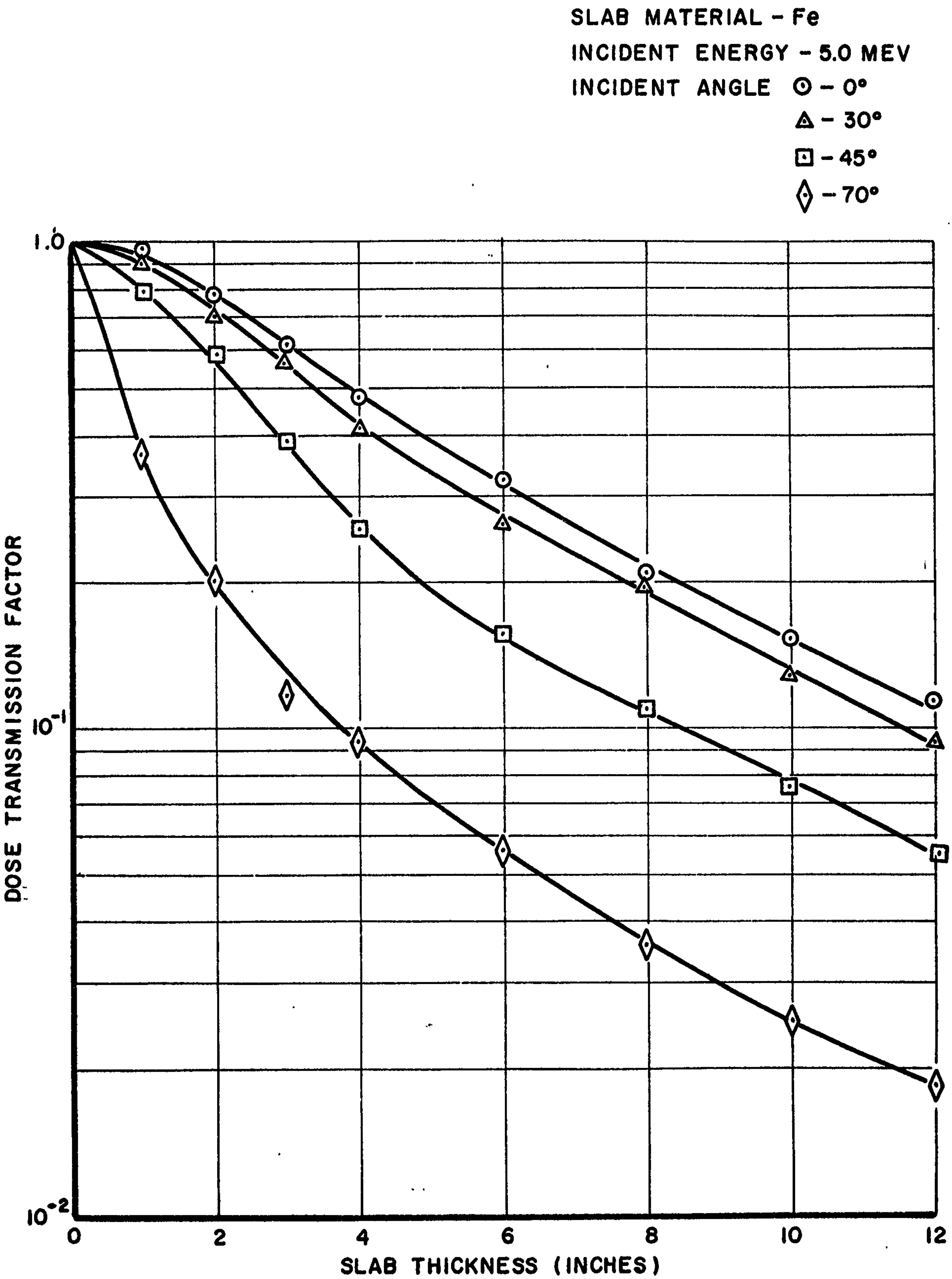


FIG. 17 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE



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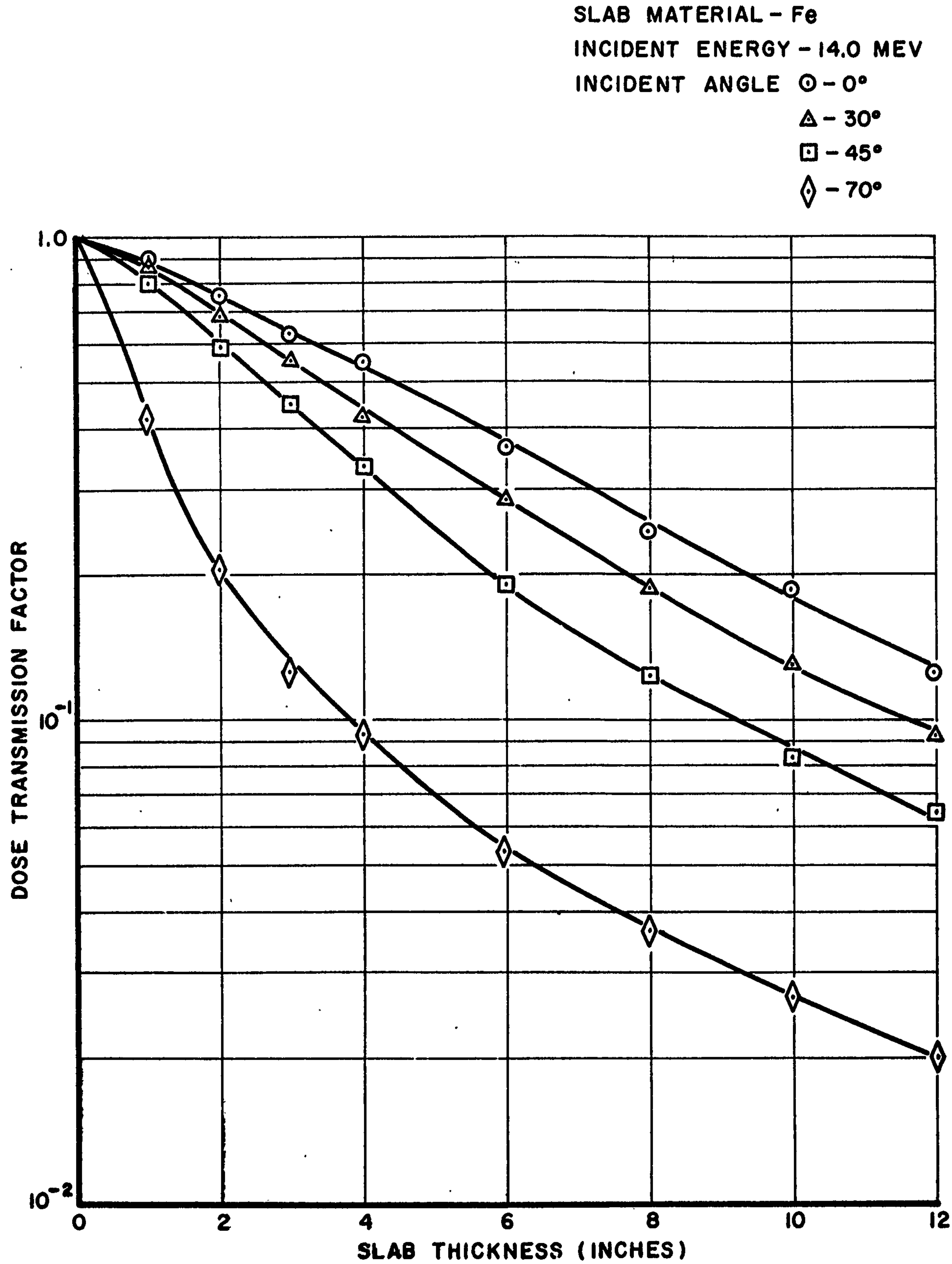

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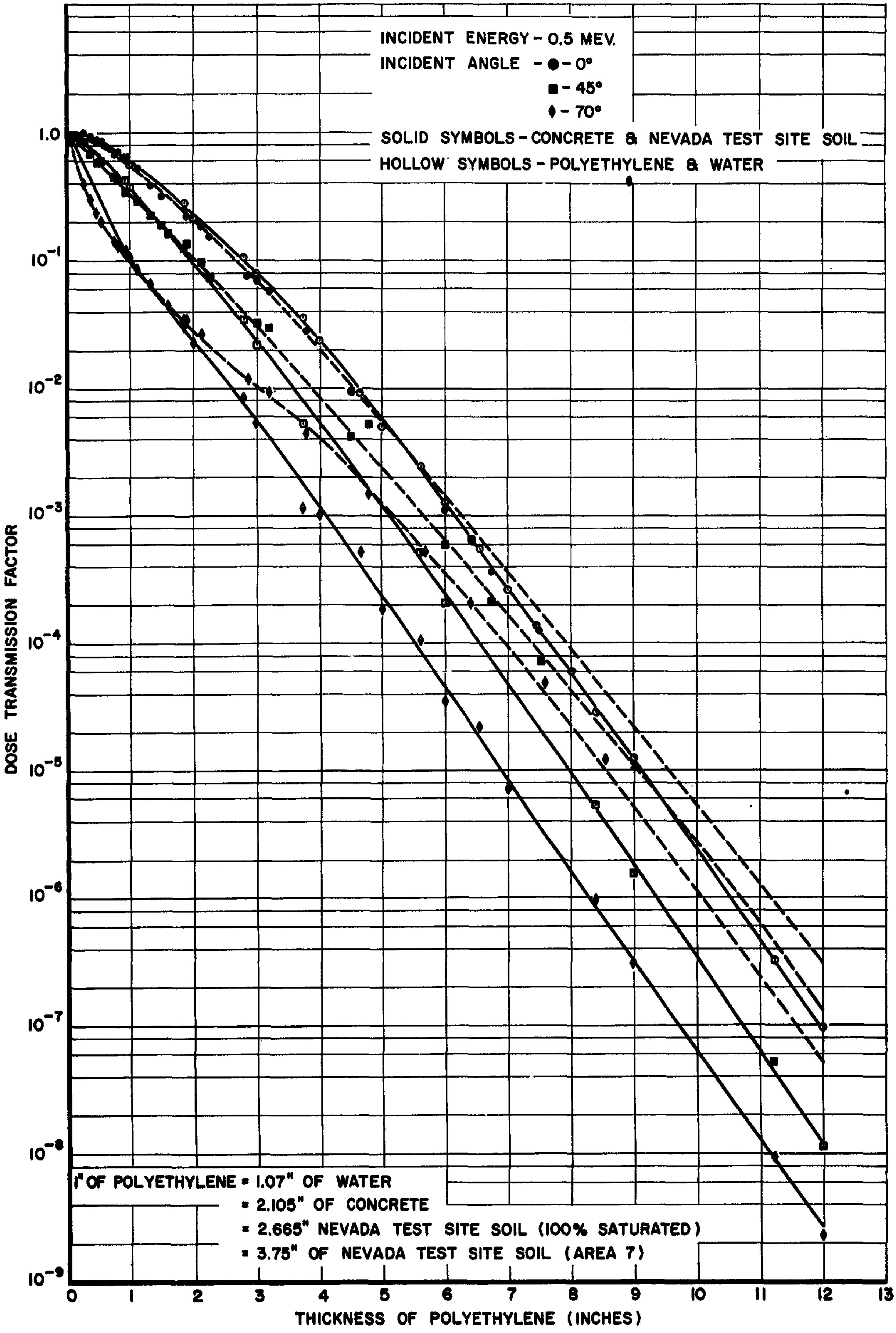


FIG. 20 NEUTRON DOSE TRANSMISSION
AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

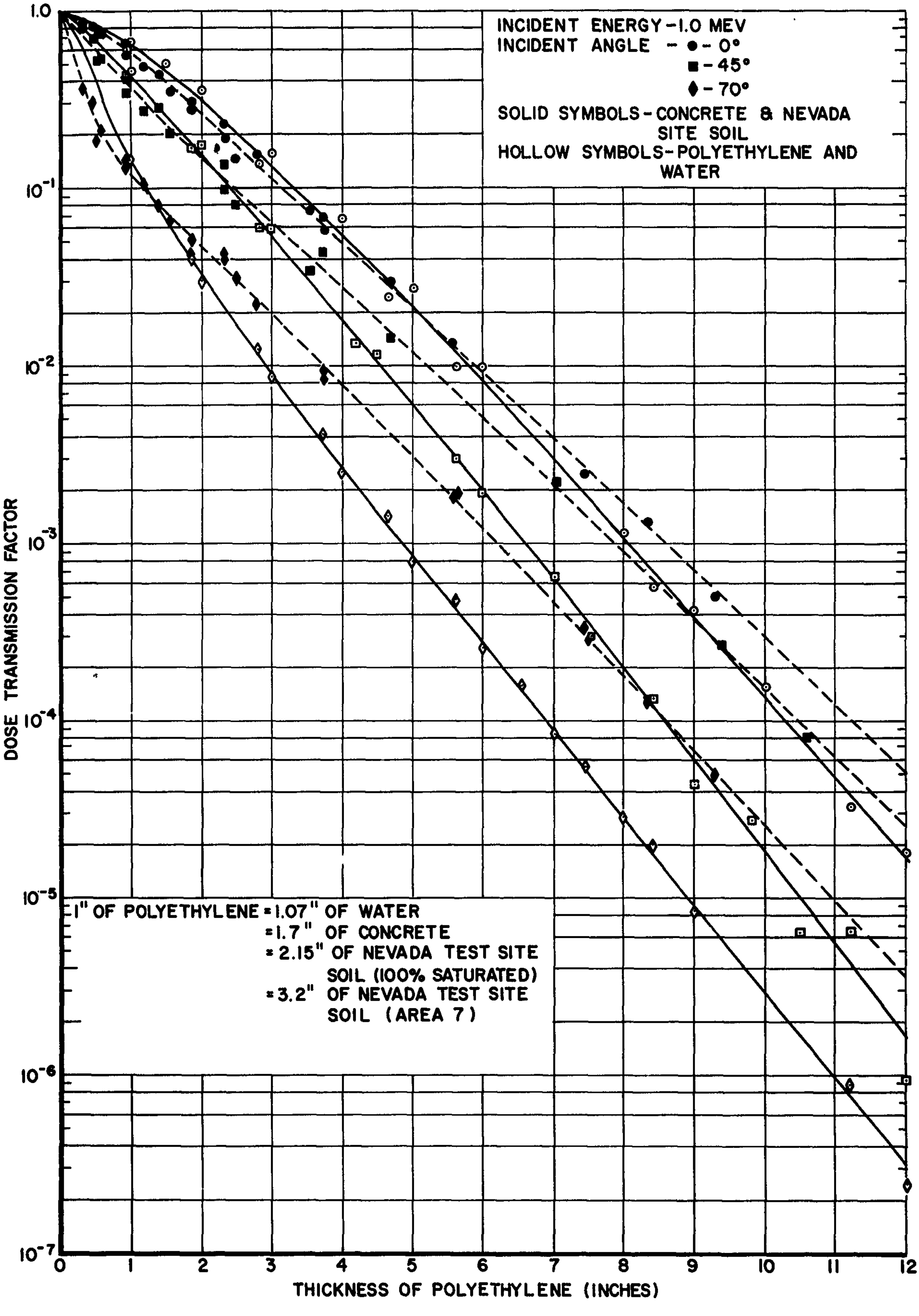


FIG. 21 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

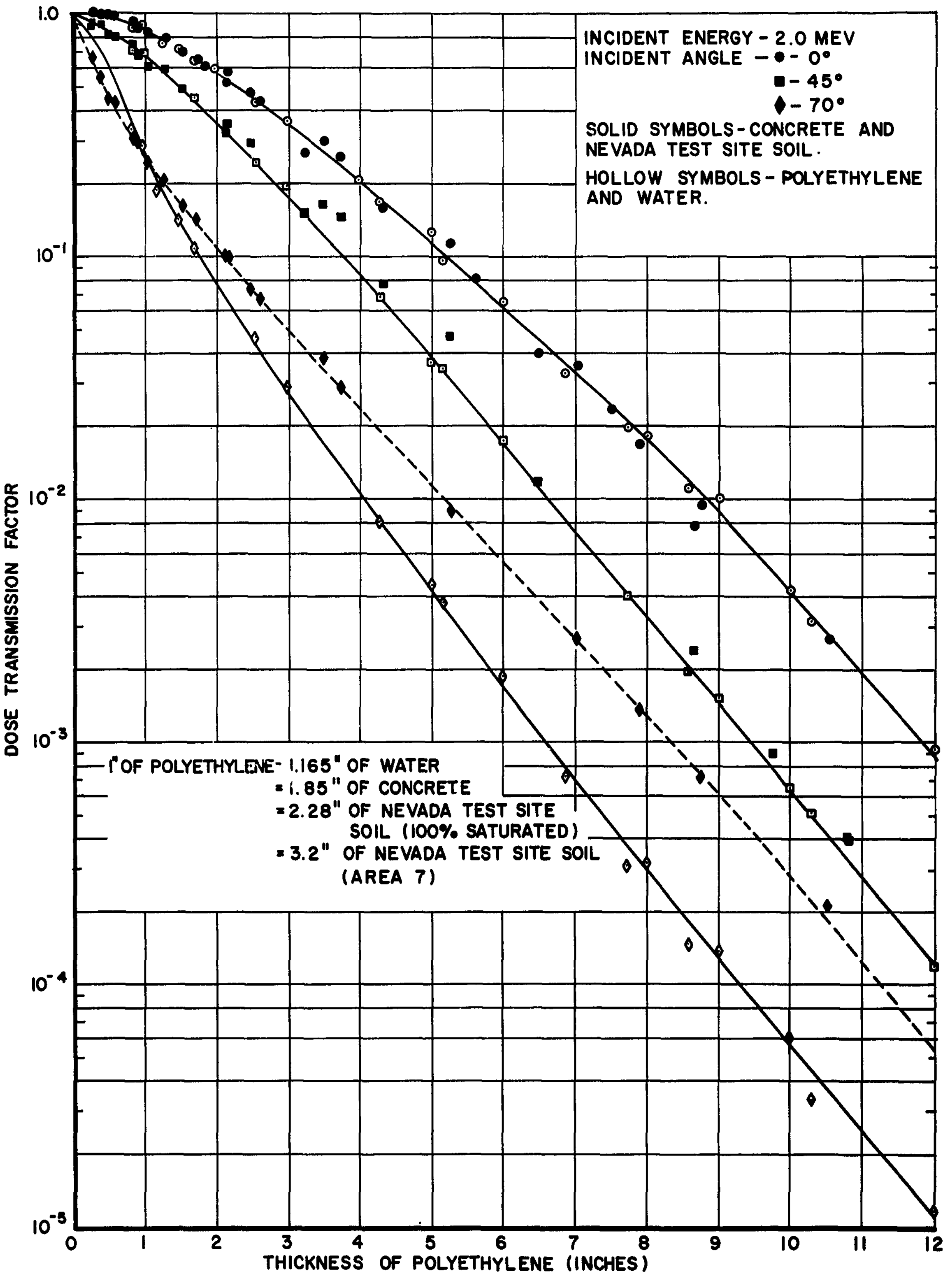


FIG. 22 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

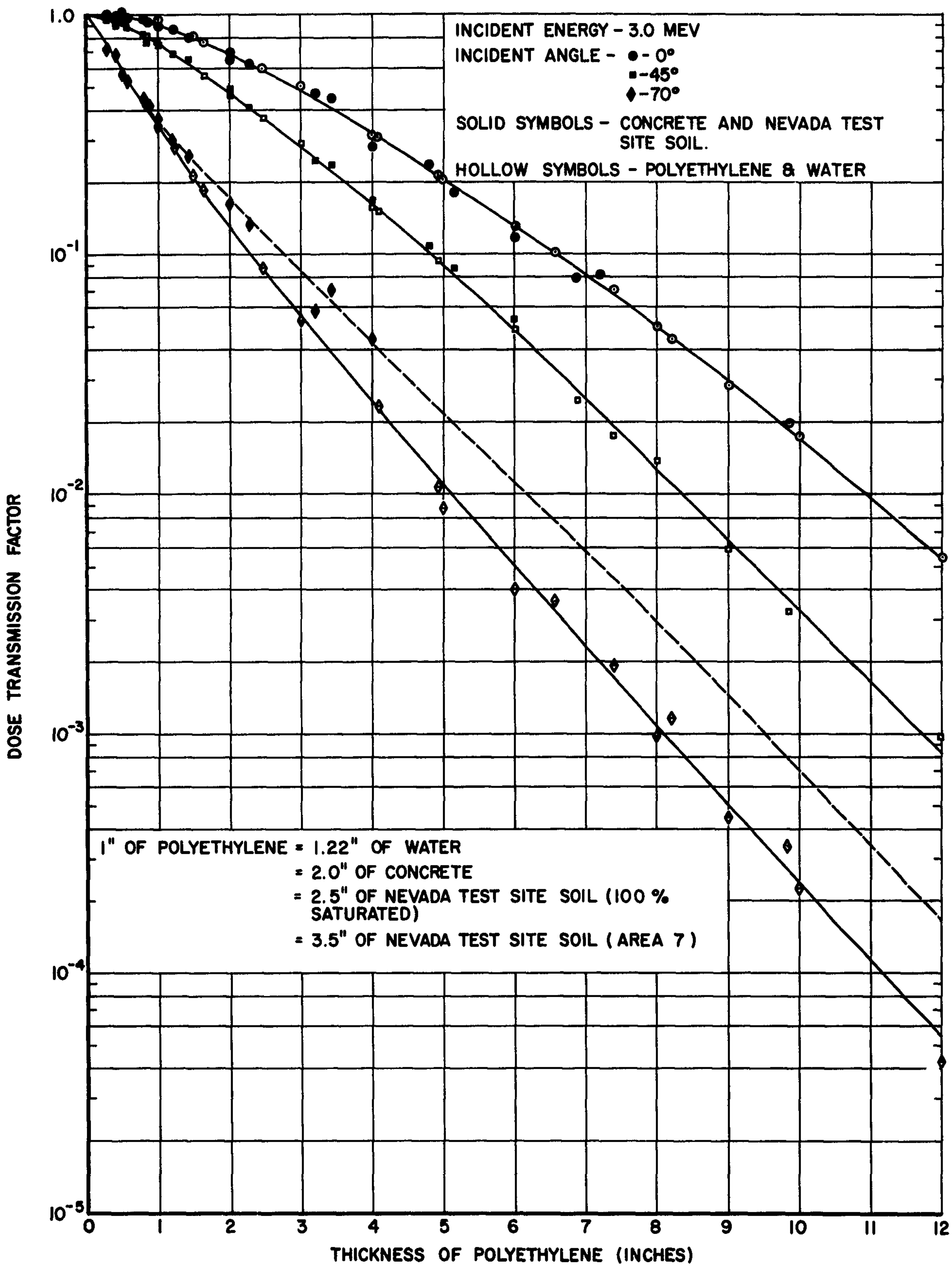


FIG. 23 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

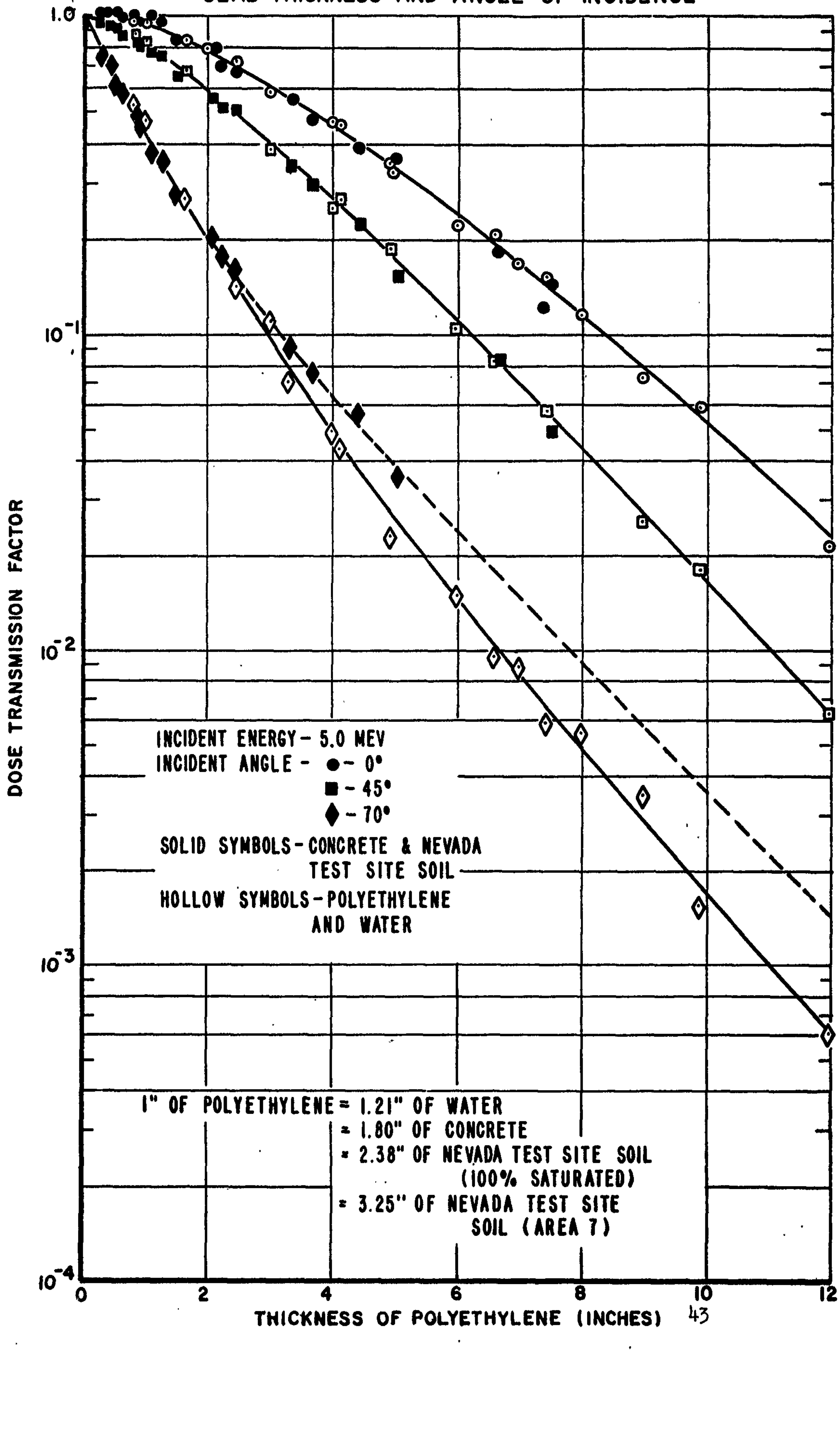


FIG. 24 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND ANGLE OF INCIDENCE

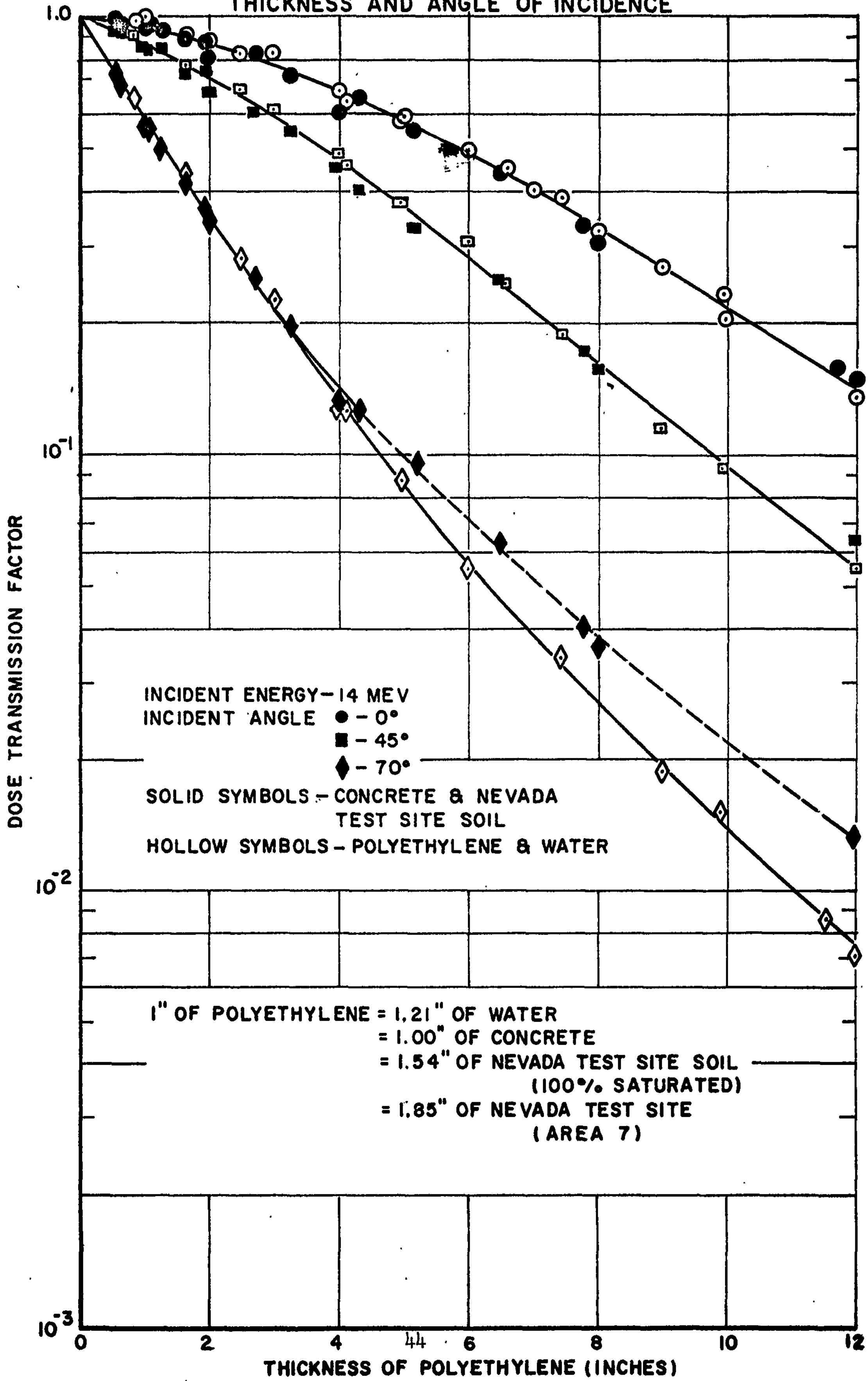


FIG. 25 DOSE TRANSMISSION FACTOR VS. TOTAL THICKNESS OF IRON

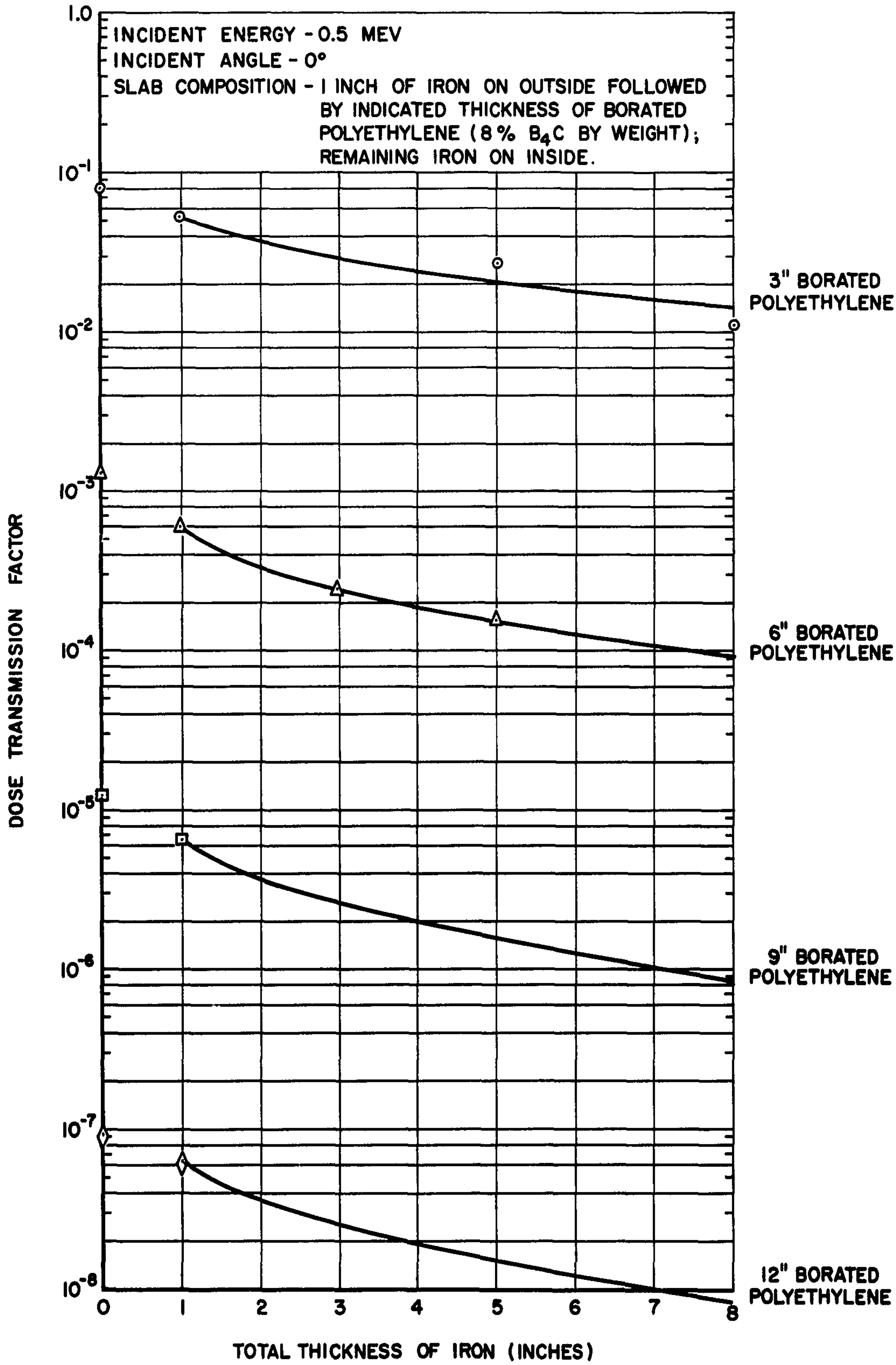


FIG. 26 DOSE TRANSMISSION FACTOR VS. TOTAL THICKNESS OF IRON

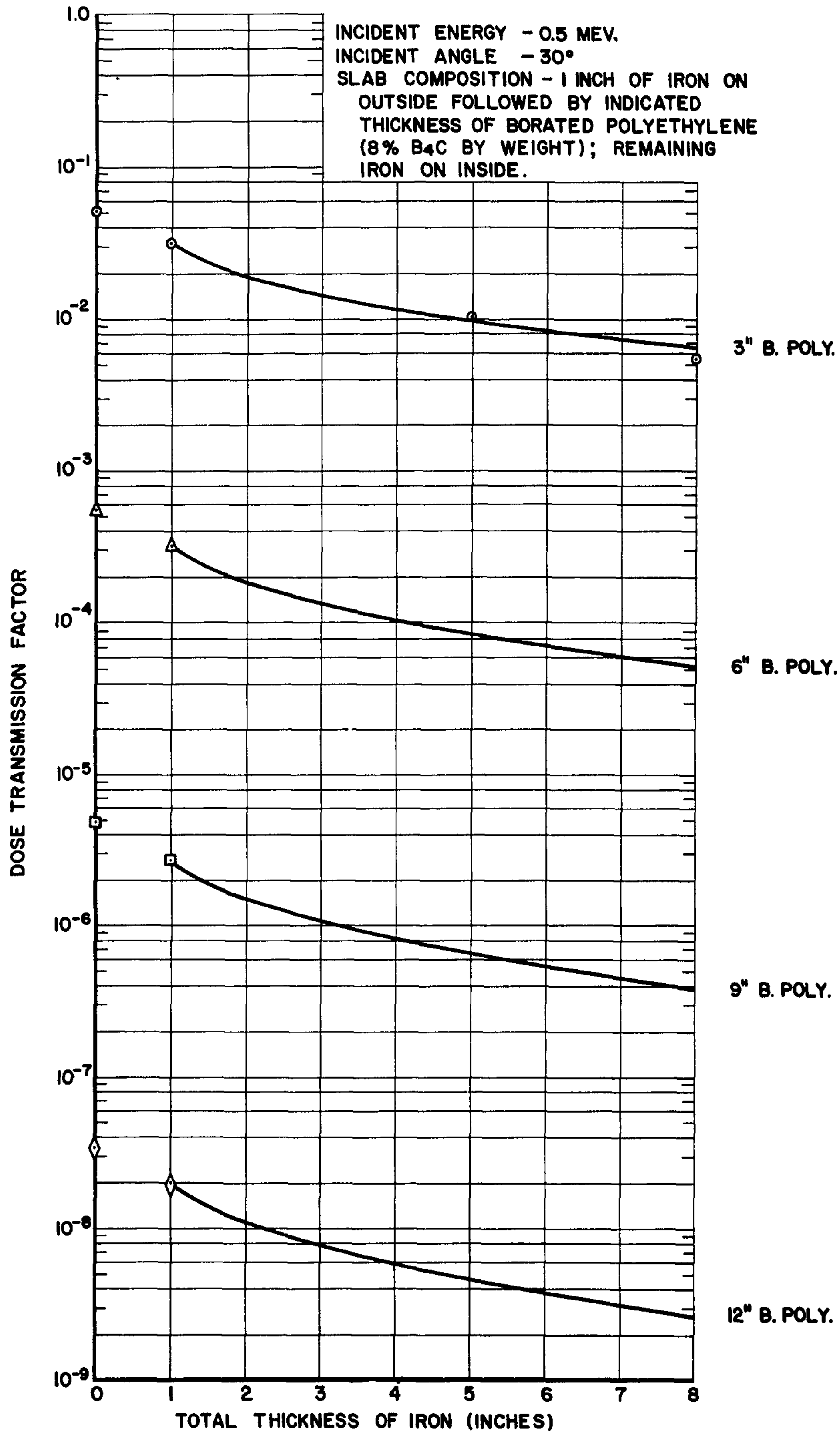


FIG. 27 DOSE TRANSMISSION FACTOR VS. TOTAL THICKNESS OF IRON

INCIDENT ENERGY – 0.5 MEV
INCIDENT ANGLE – – 70°
SLAB COMPOSITION – 1 INCH OF IRON ON OUTSIDE FOLLOWED BY INDICATED THICKNESS OF BORATED POLYETHYLENE (8 % B_4C BY WEIGHT); REMAINING IRON ON INSIDE.

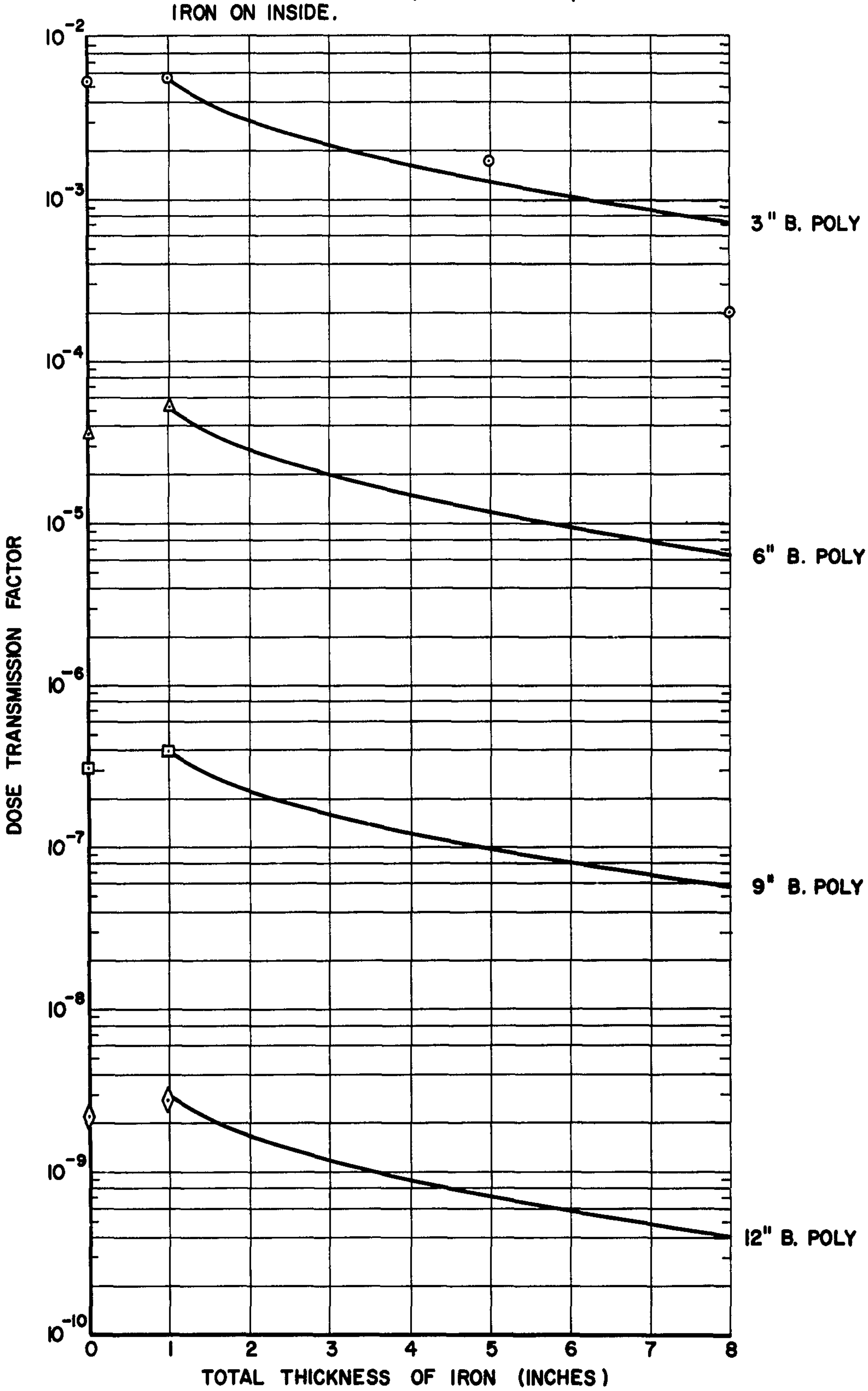


FIG. 28 DOSE TRANSMISSION FACTOR VS. TOTAL THICKNESS OF IRON

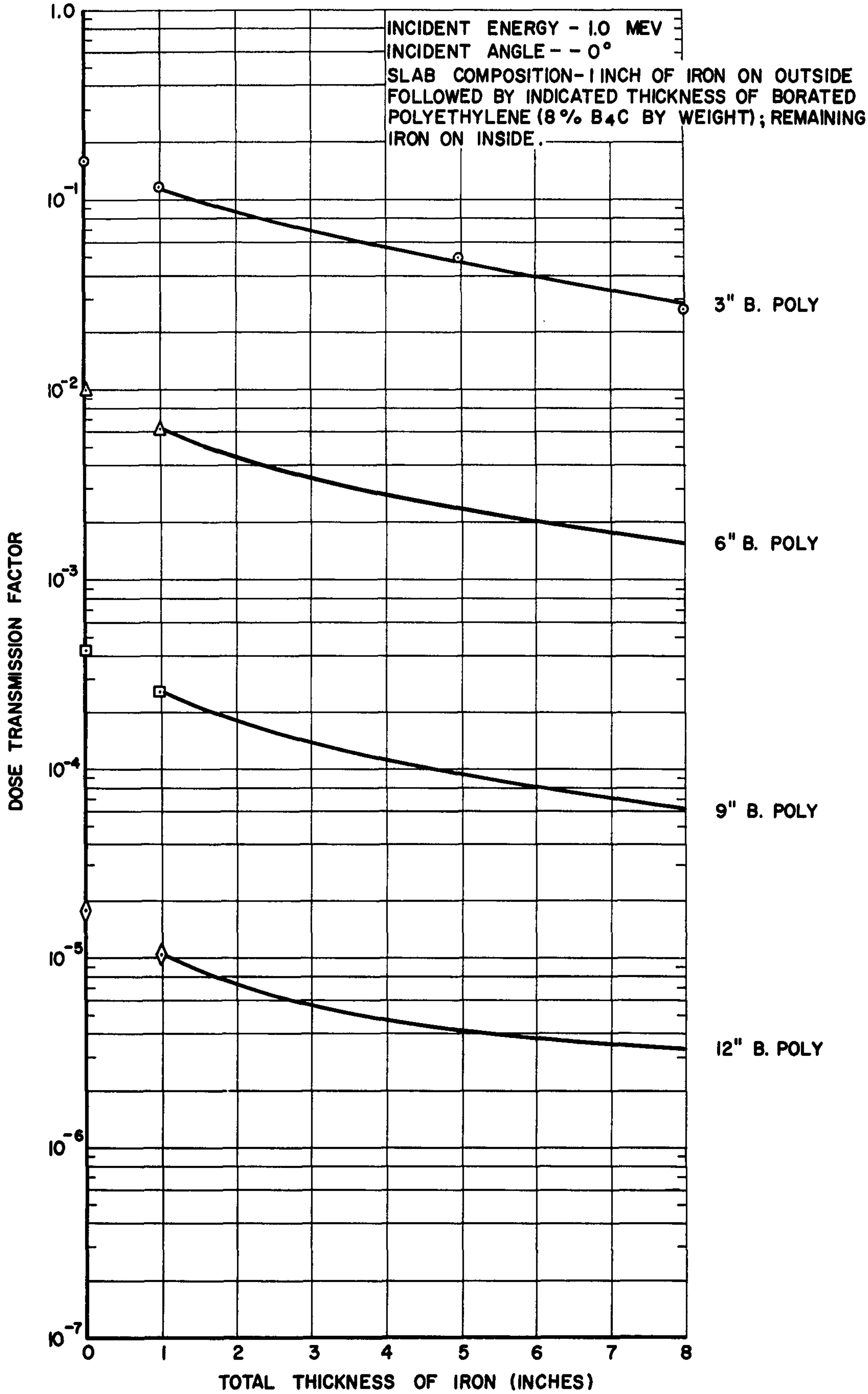


FIG. 29 DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

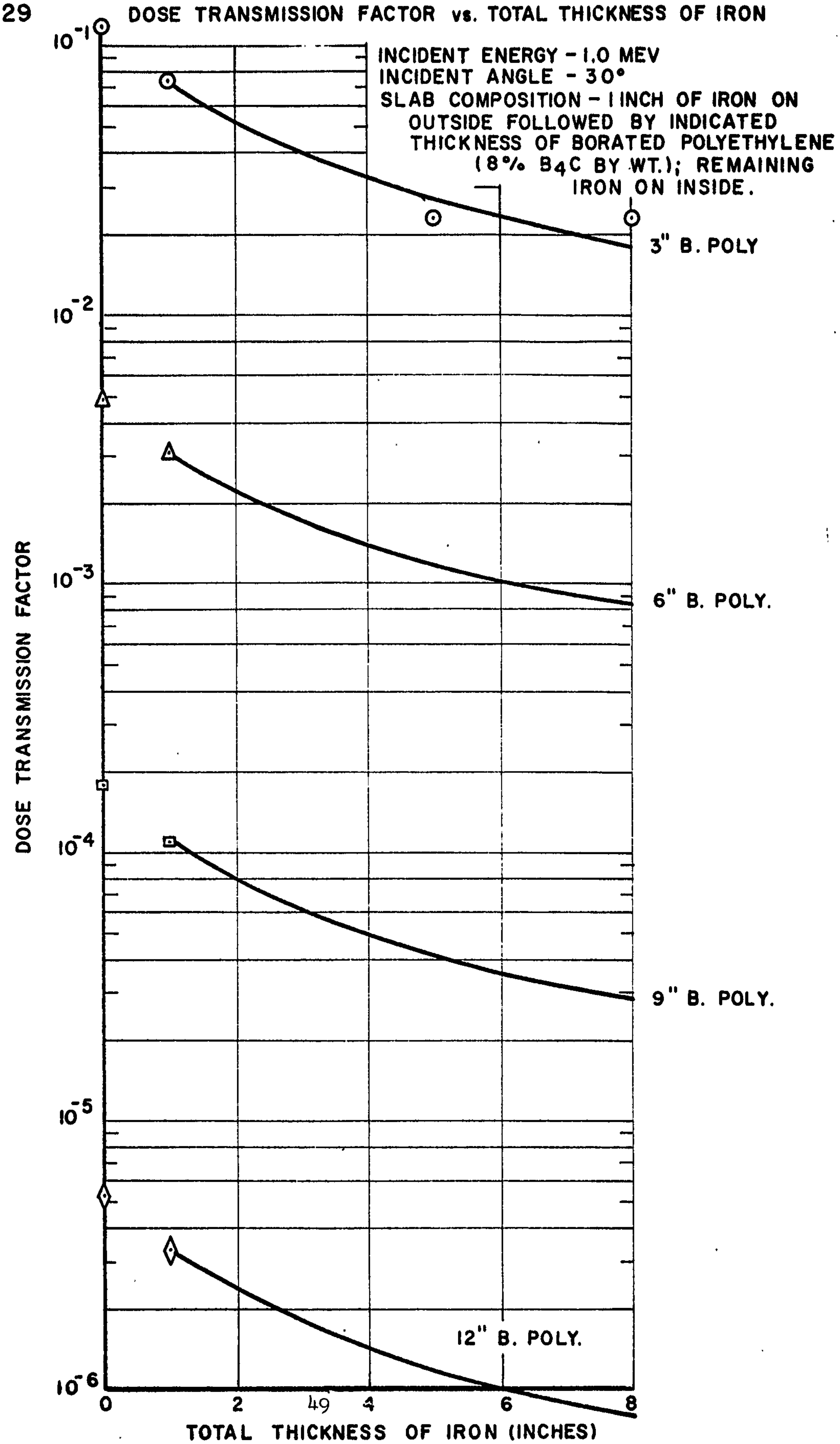


FIG. 30 DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

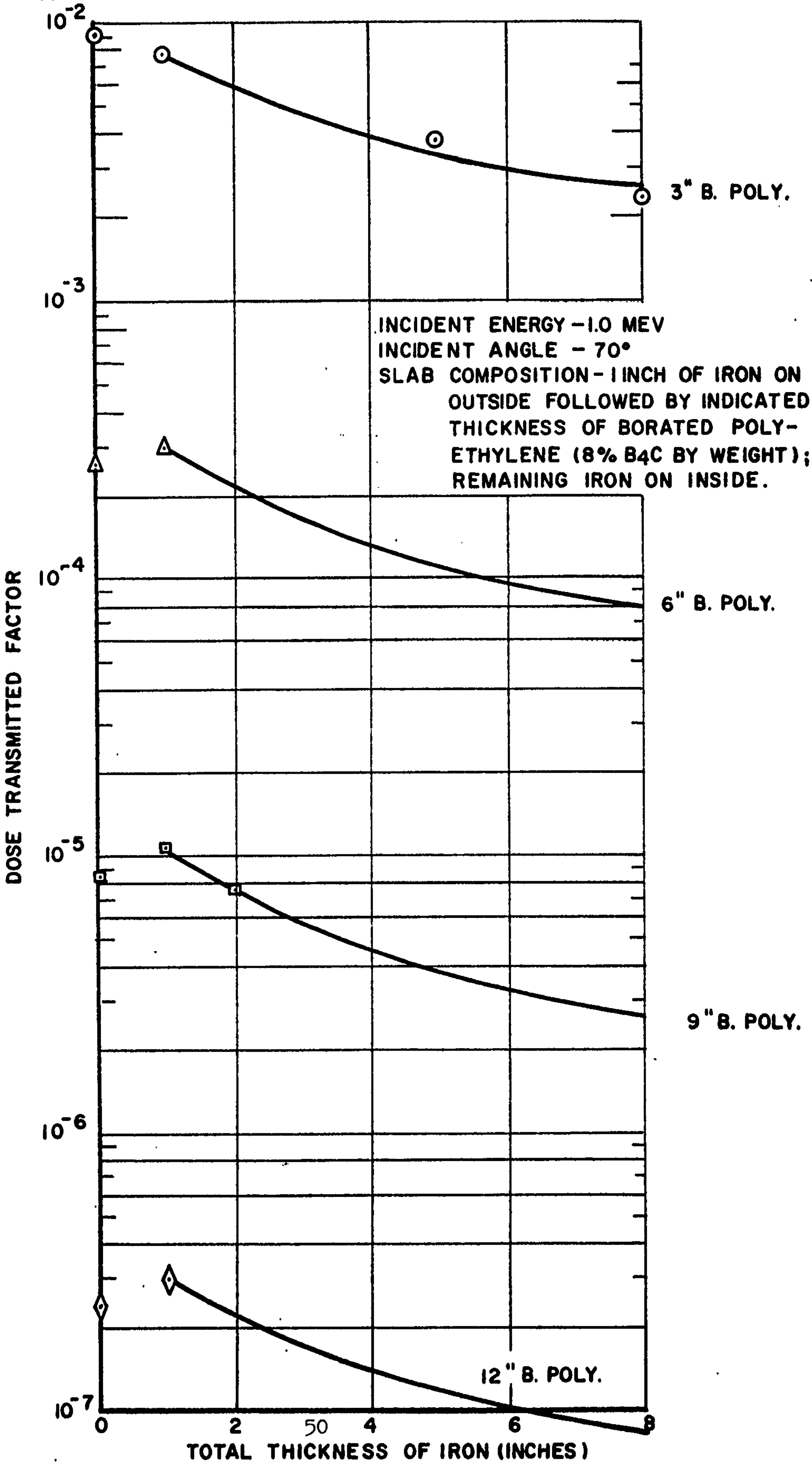


FIG. 31 DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

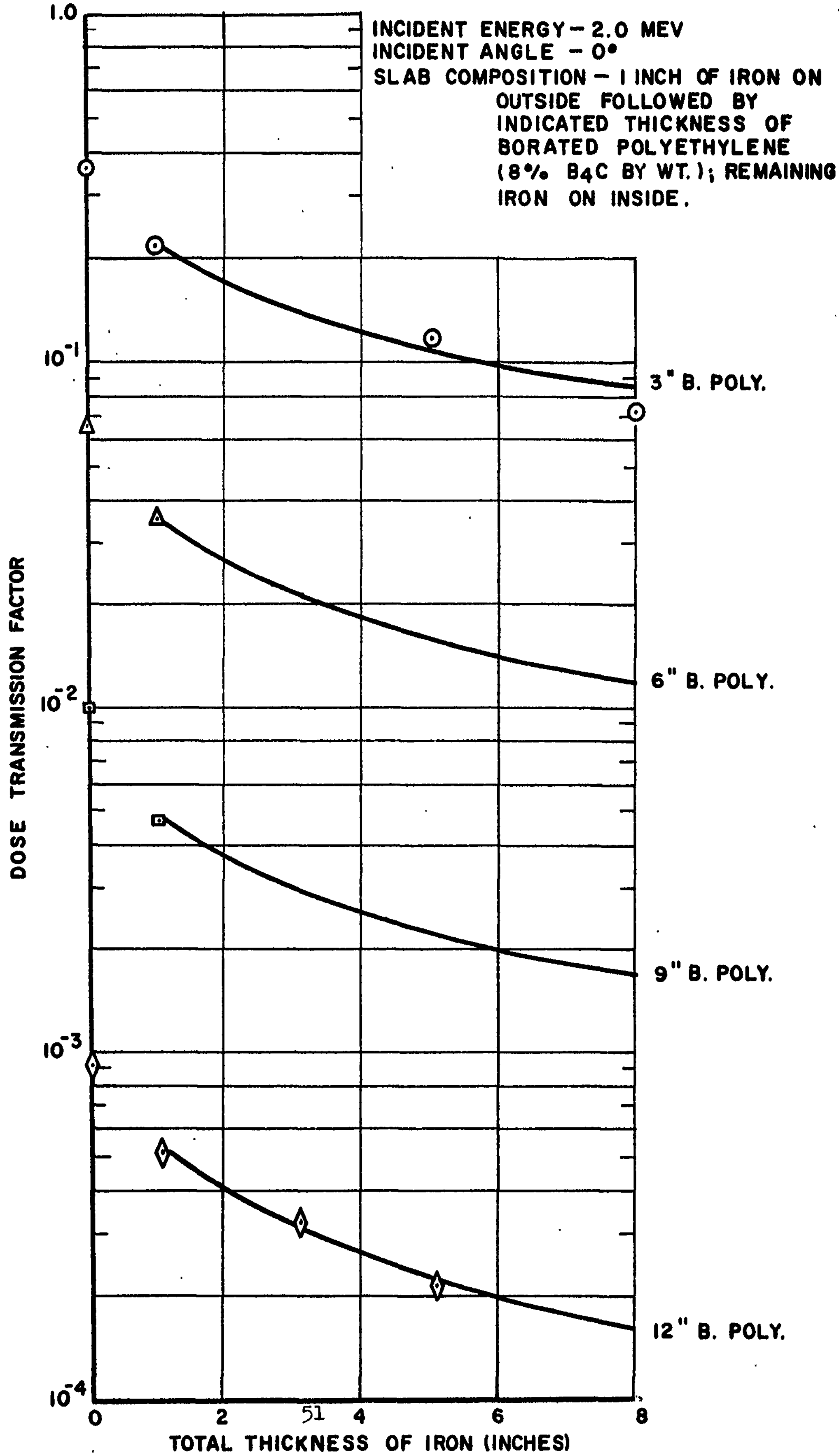


FIG. 32 DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

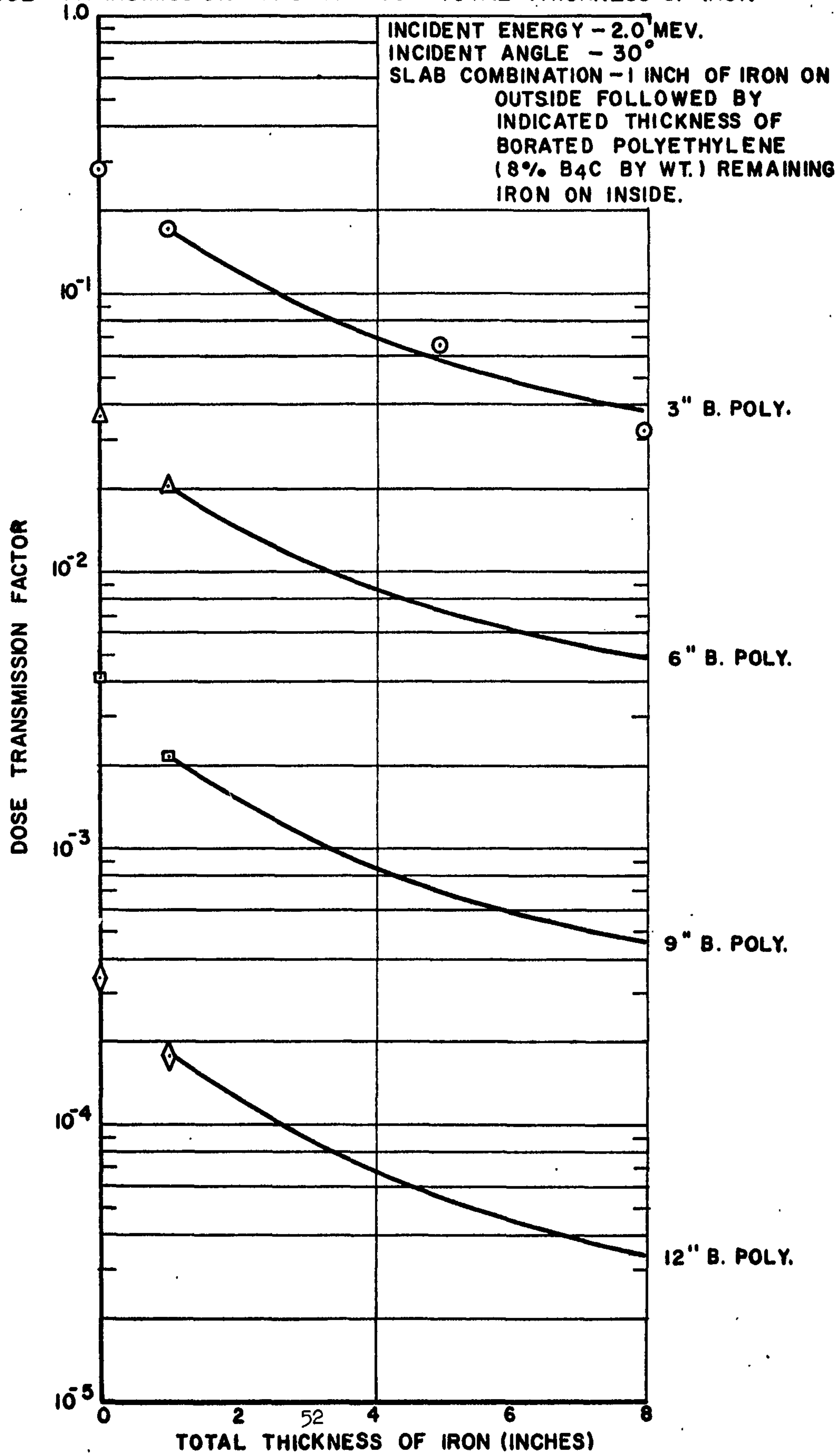


FIG. 33 DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

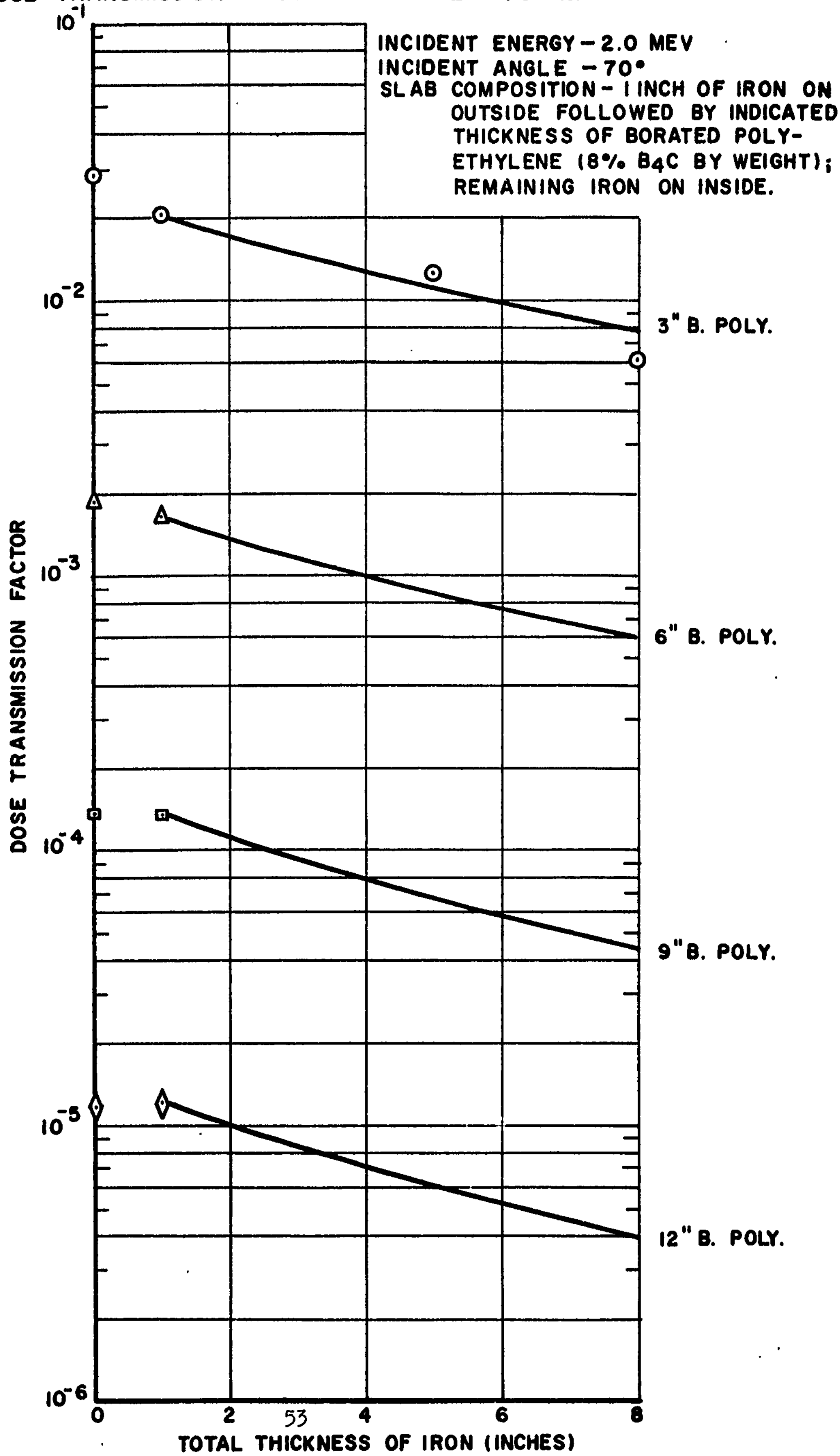


FIG. 34 . DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

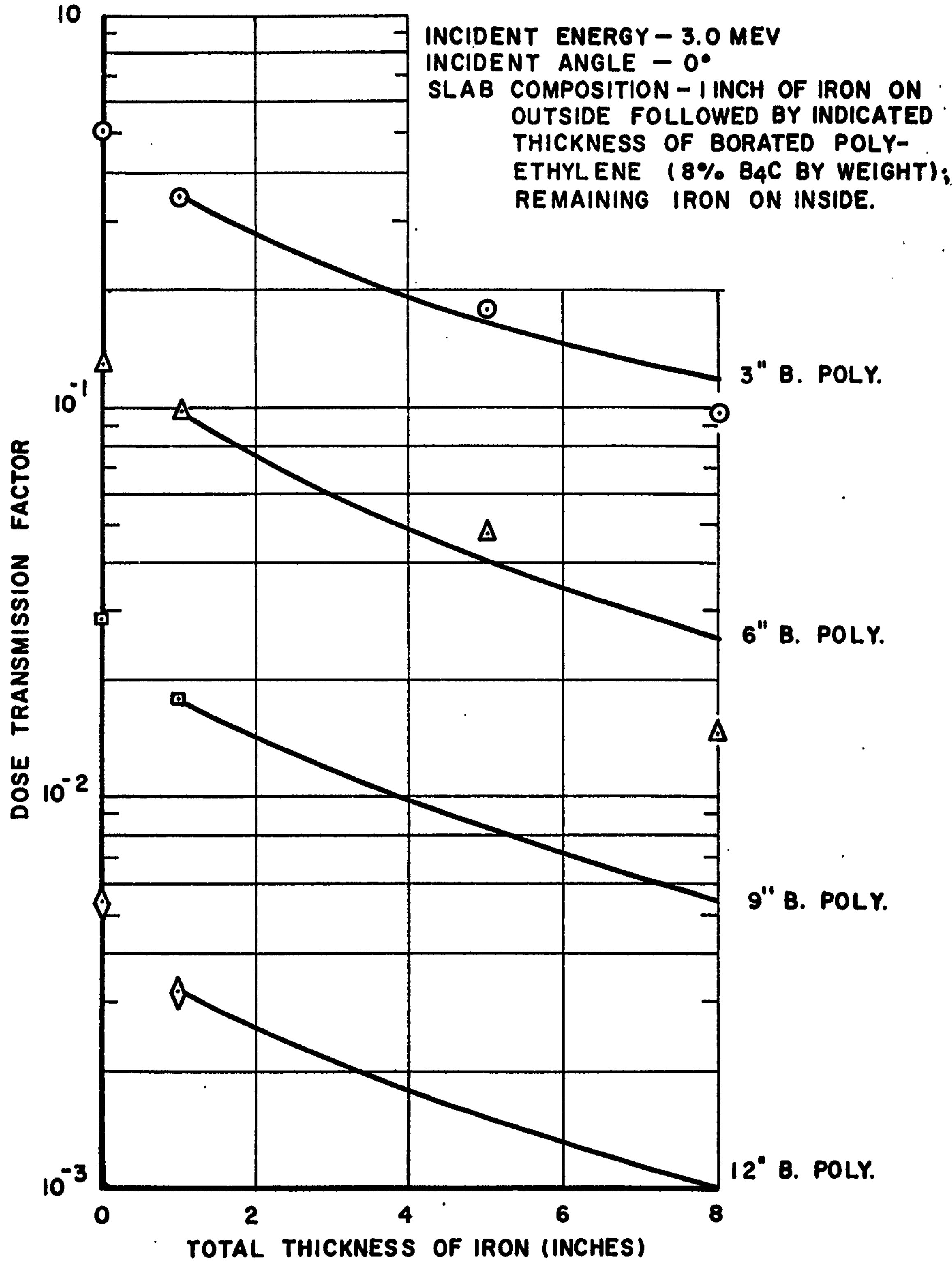


FIG. 35 DOSE TRANSMISSION FACTOR VS. TOTAL THICKNESS OF IRON

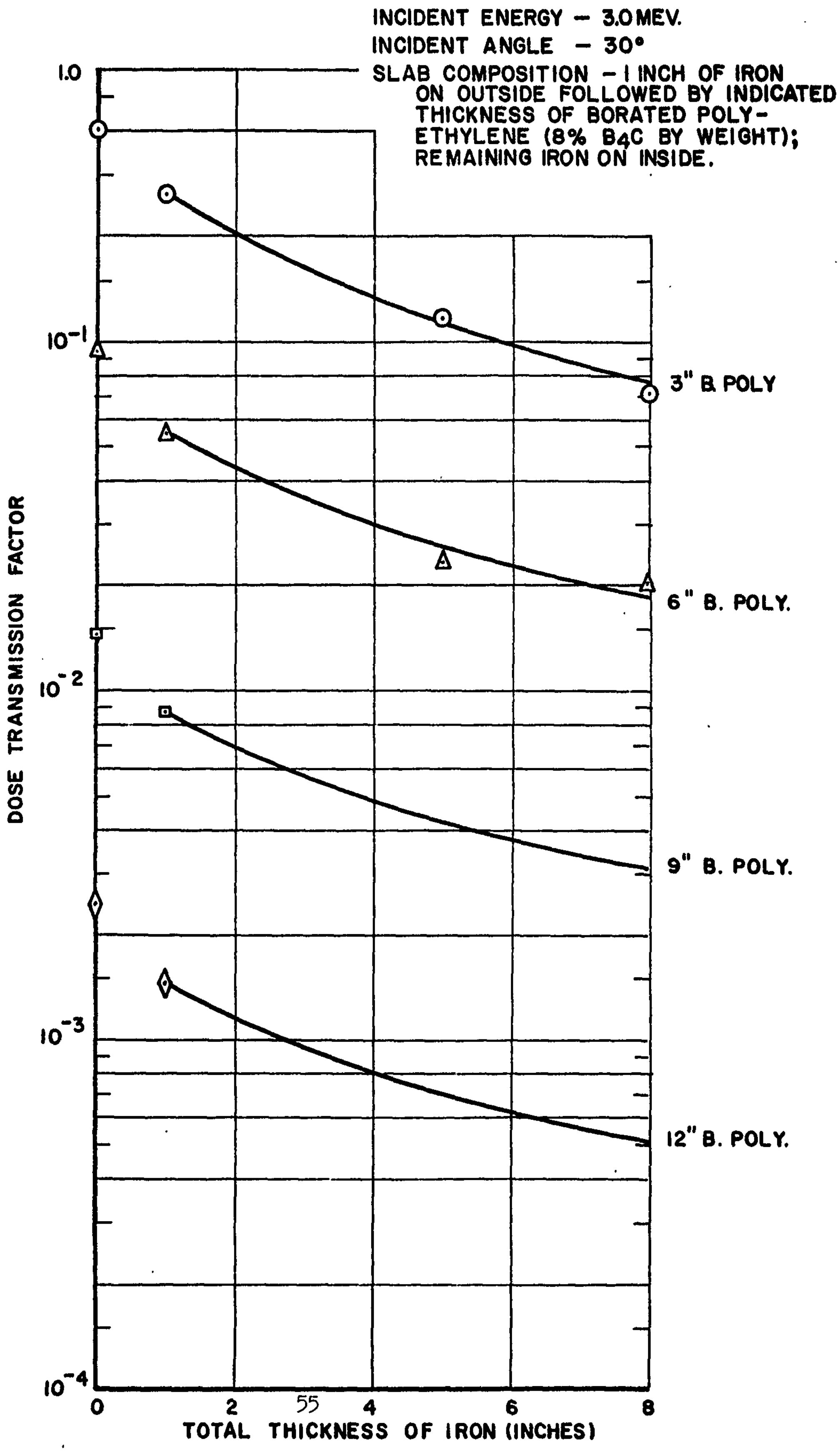


FIG. 36 DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

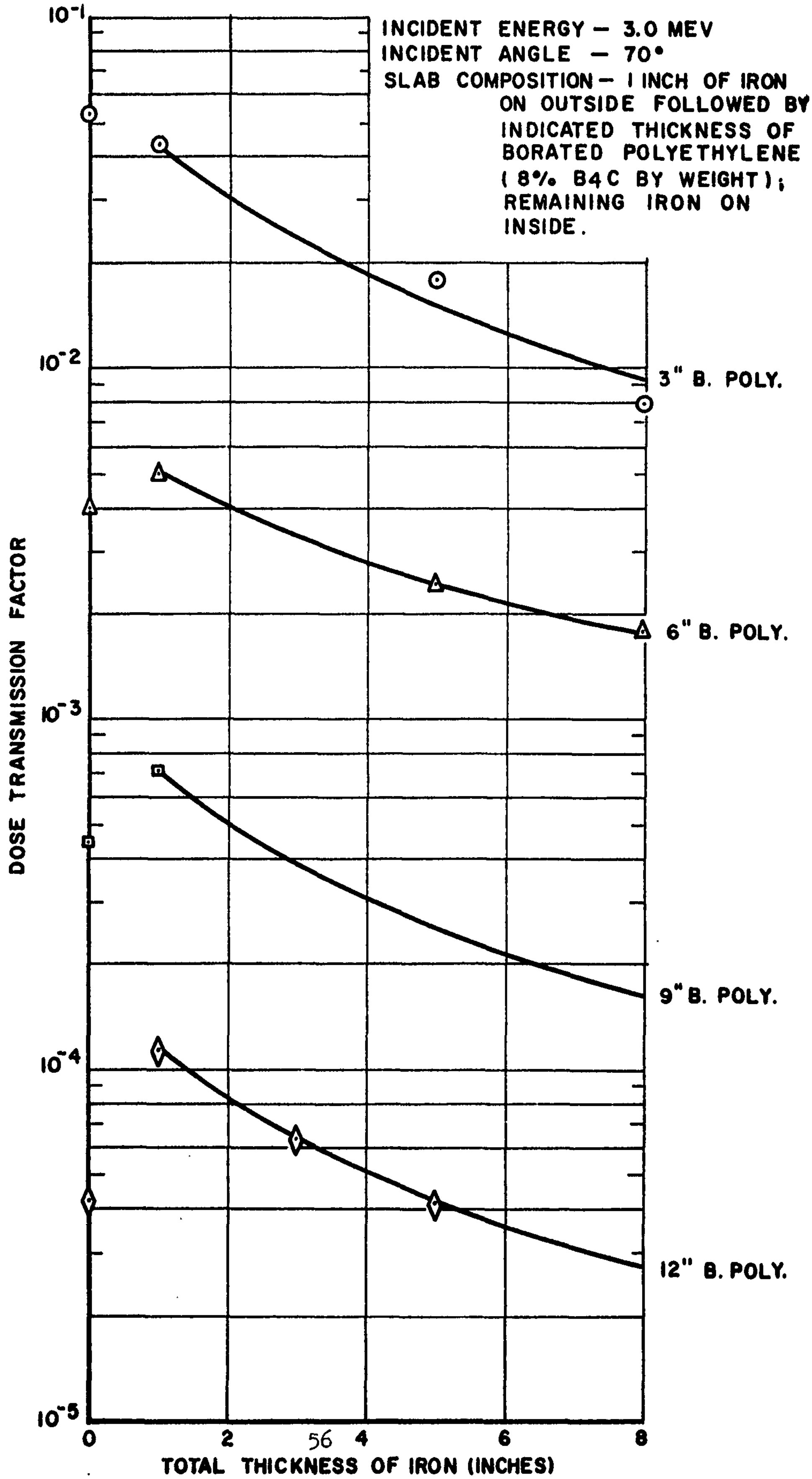


FIG. 37 DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

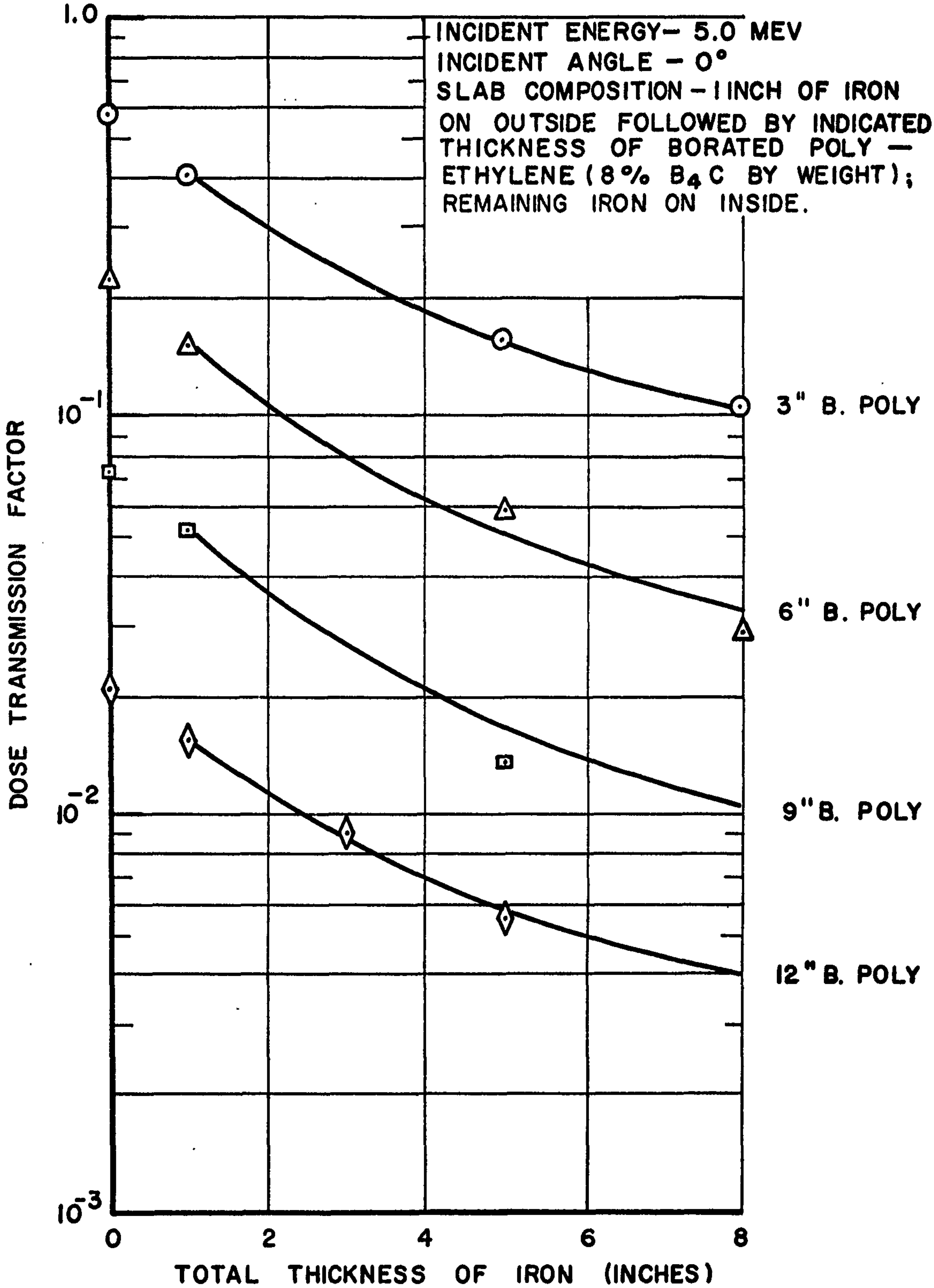


FIG. 38 DOSE TRANSMISSION FACTOR Vs. TOTAL THICKNESS OF IRON

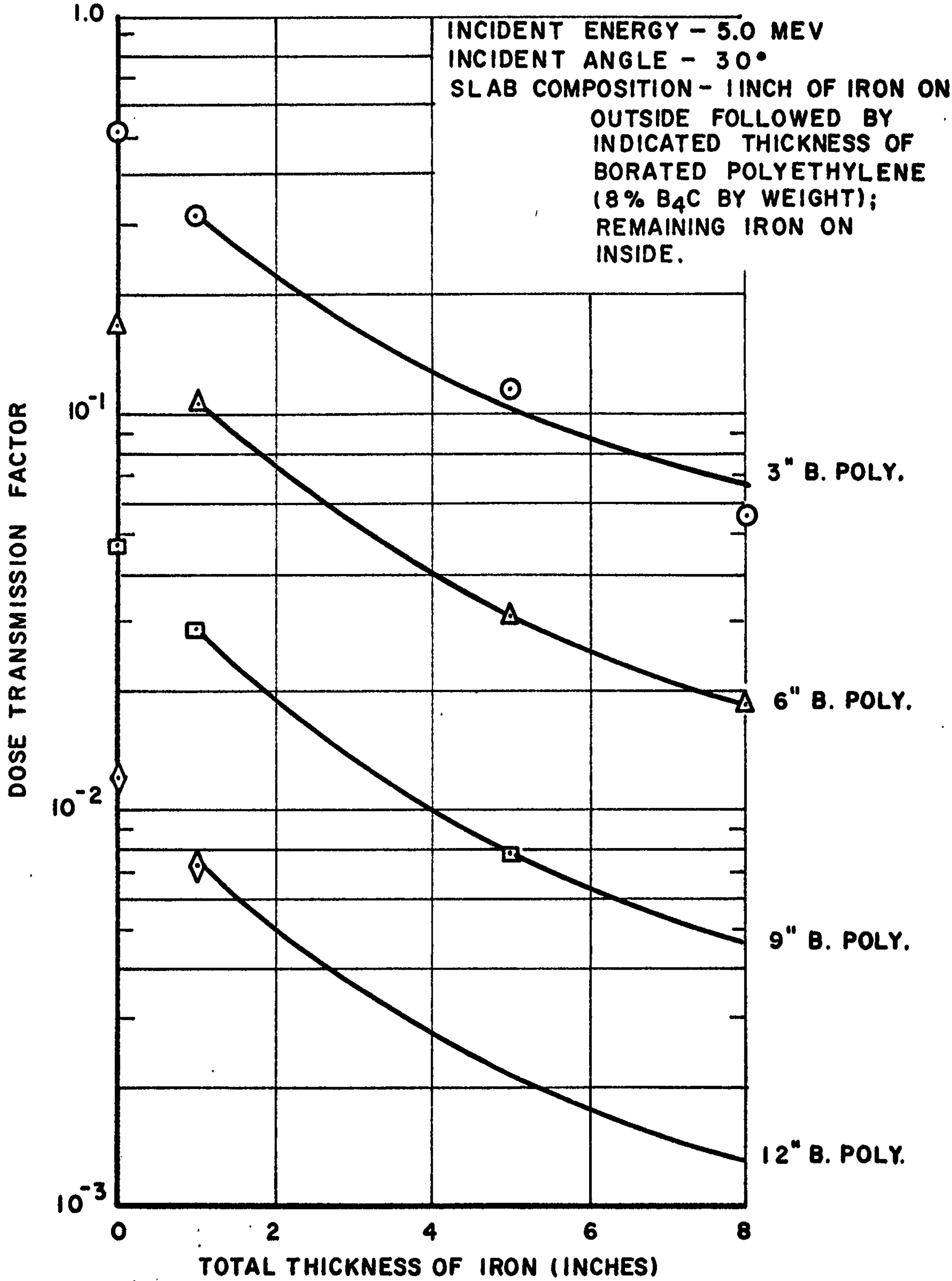


FIG. 39 DOSE TRANSMISSION FACTOR VS. TOTAL THICKNESS OF IRON

INCIDENT ENERGY — 5.0 MEV
INCIDENT ANGLE — 70°
SLAB COMPOSITION — 1 INCH OF IRON ON OUTSIDE FOLLOWED BY INDICATED THICKNESS OF BORATED POLYETHYLENE (8% B_4C BY WEIGHT); REMAINING IRON ON INSIDE.

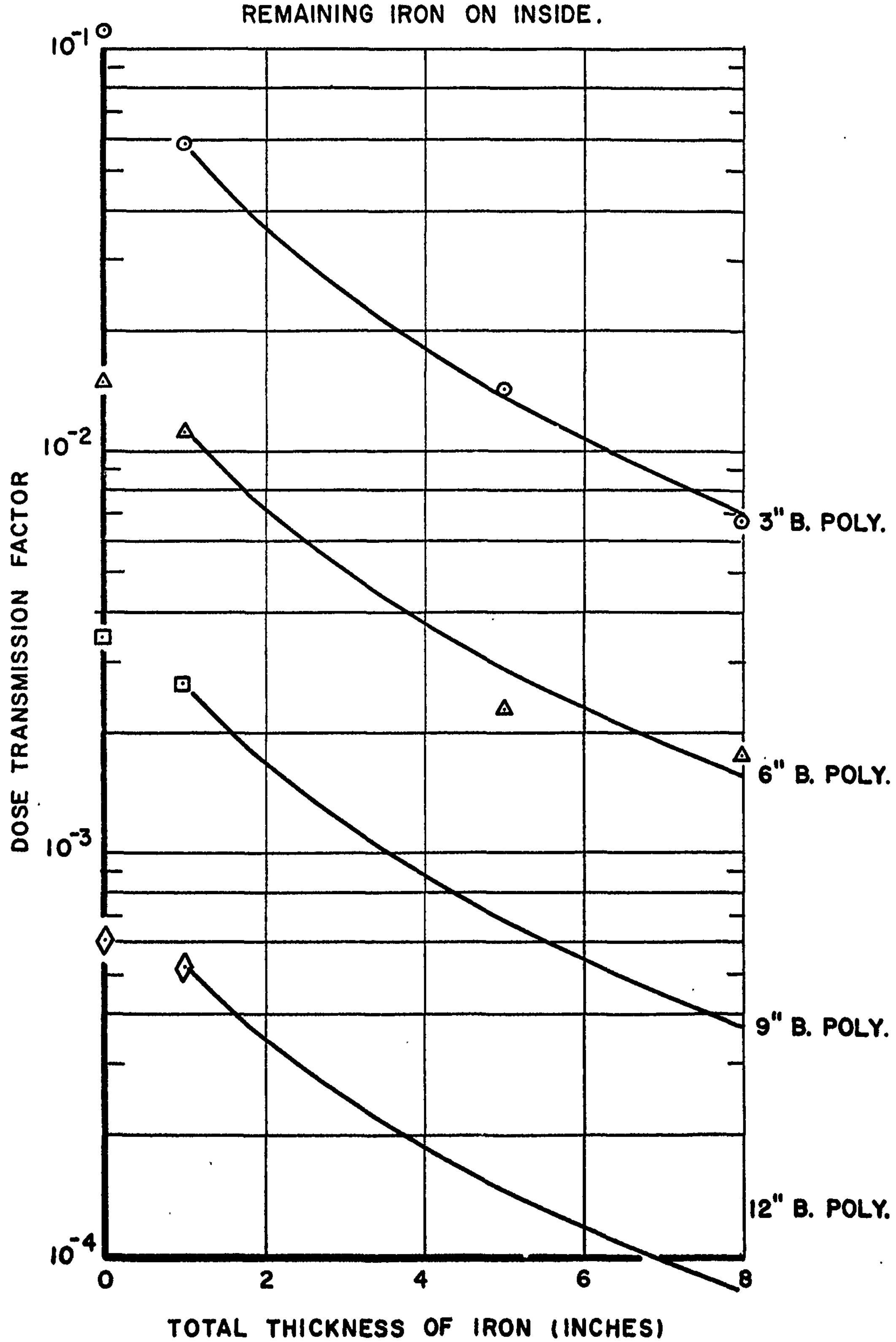


FIG. 40 DOSE TRANSMISSION FACTOR VS. TOTAL THICKNESS OF IRON

INCIDENT ENERGY - 14 MEV
INCIDENT ANGLE - 0°
SLAB COMPOSITION - 1 INCH OF IRON ON OUTSIDE FOLLOWED BY INDICATED THICKNESS OF BORATED POLYETHYLENE (8% B_4C BY WEIGHT); REMAINING IRON ON INSIDE.

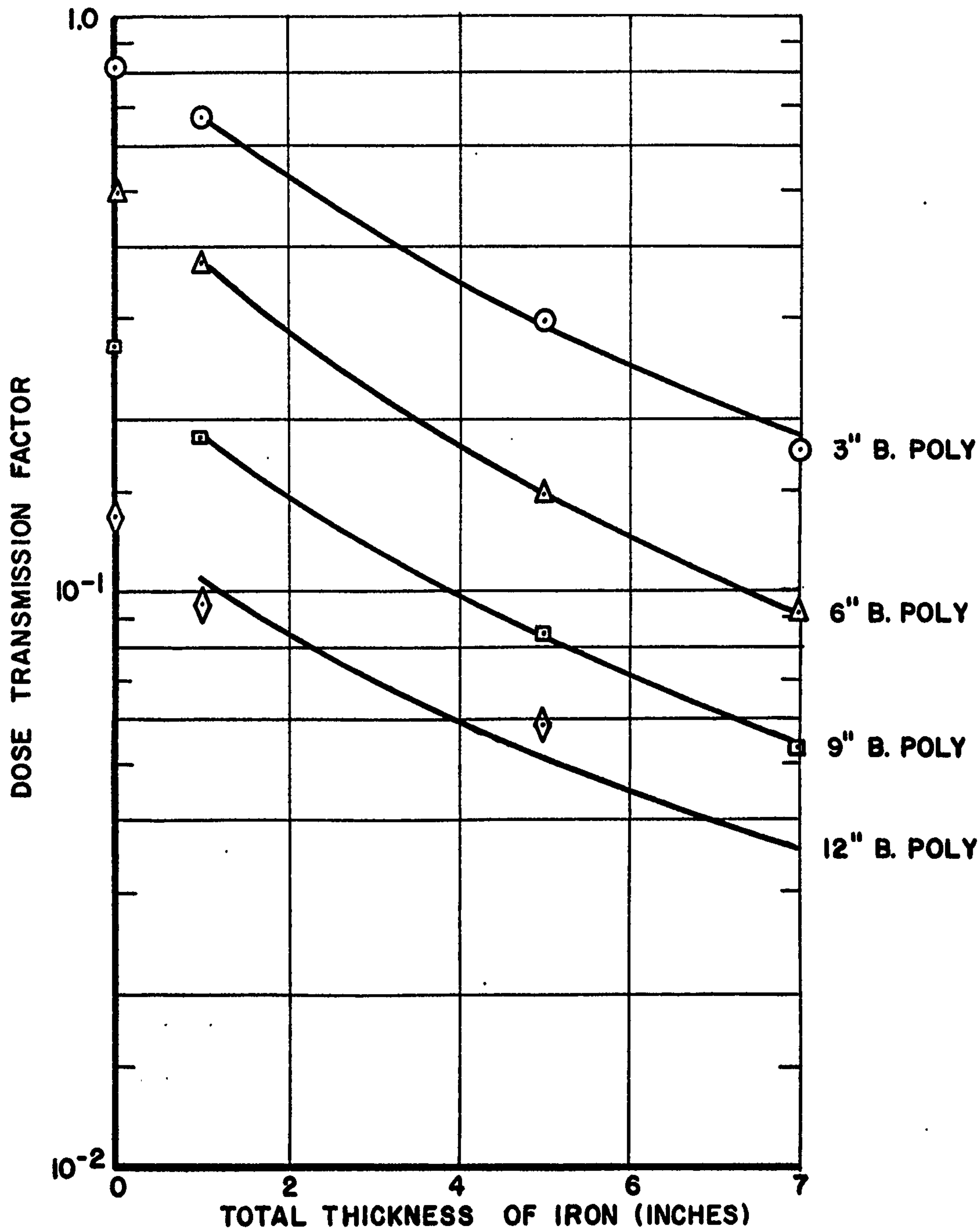


FIG. 41 DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

INCIDENT ENERGY – 14 MEV.
INCIDENT ANGLE – 30°
SLAB COMPOSITION – 1 INCH OF IRON ON OUTSIDE
FOLLOWED BY INDICATED THICKNESS OF BORATED
POLYETHYLENE (8% B4C BY WEIGHT);
REMAINING IRON ON INSIDE

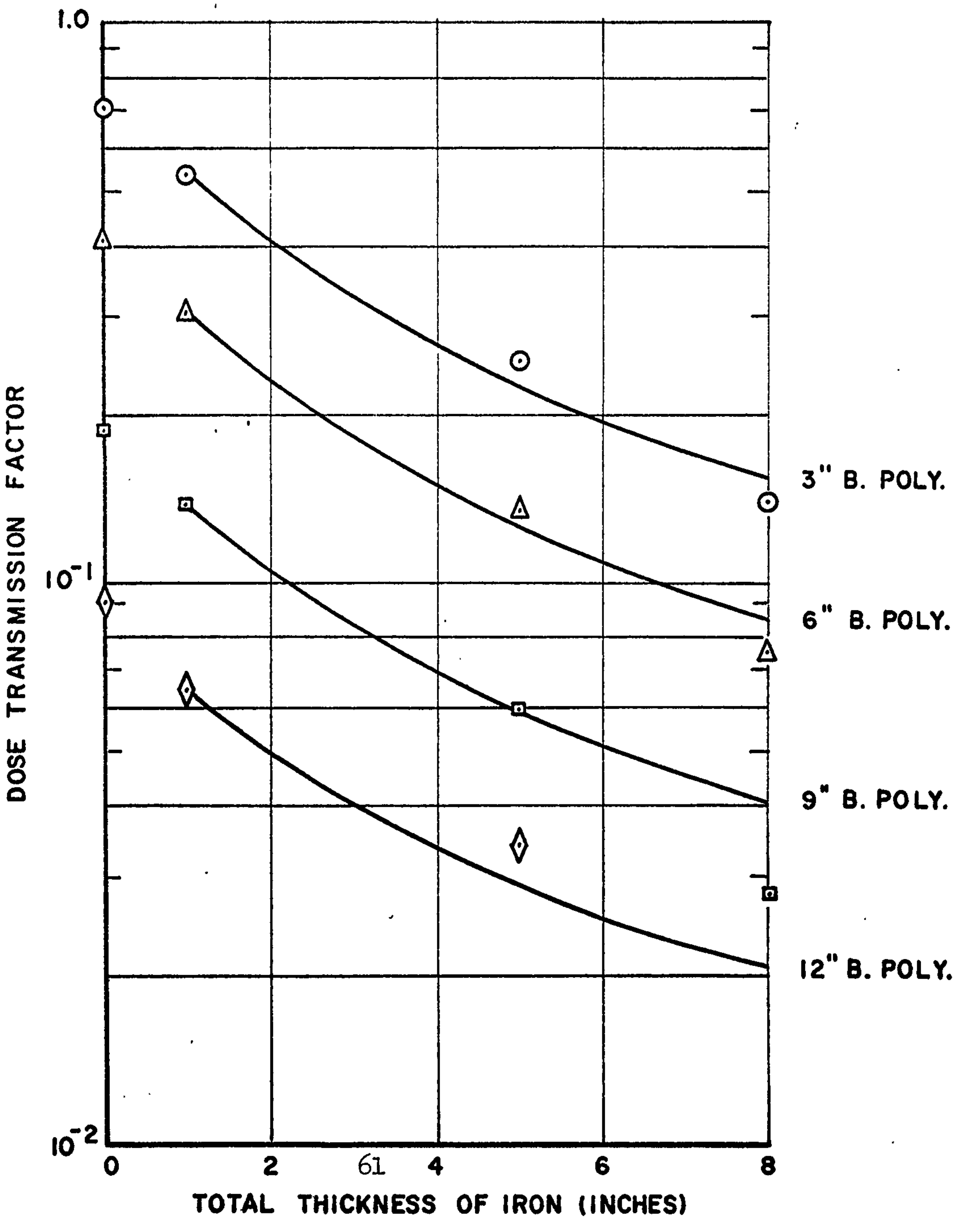


FIG. 42 DOSE TRANSMISSION FACTOR vs. TOTAL THICKNESS OF IRON

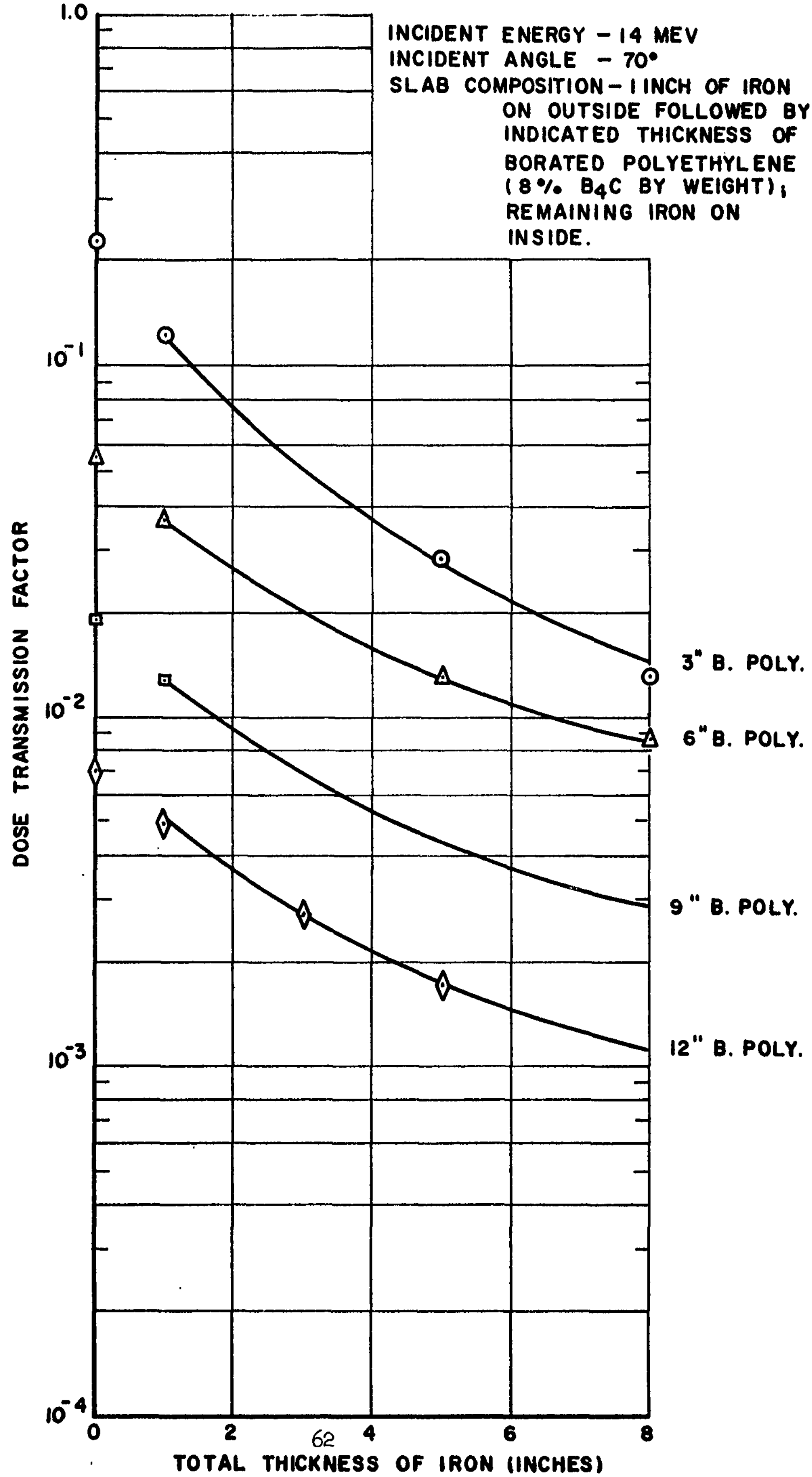


FIG. 43 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND INCIDENT ENERGY

INCIDENT ANGLE — 0°

SLAB MATERIALS — WATER — INDICATED BY SOLID SYMBOLS & SOLID LINES

BORATED POLYETHYLENE (8 % B_4C BY WEIGHT) — INDICATED BY HOLLOW SYMBOLS & DASHED LINES

INCIDENT ENERGY — ● 1 MEV; ▲ 2 MEV ; ■ 3 MEV

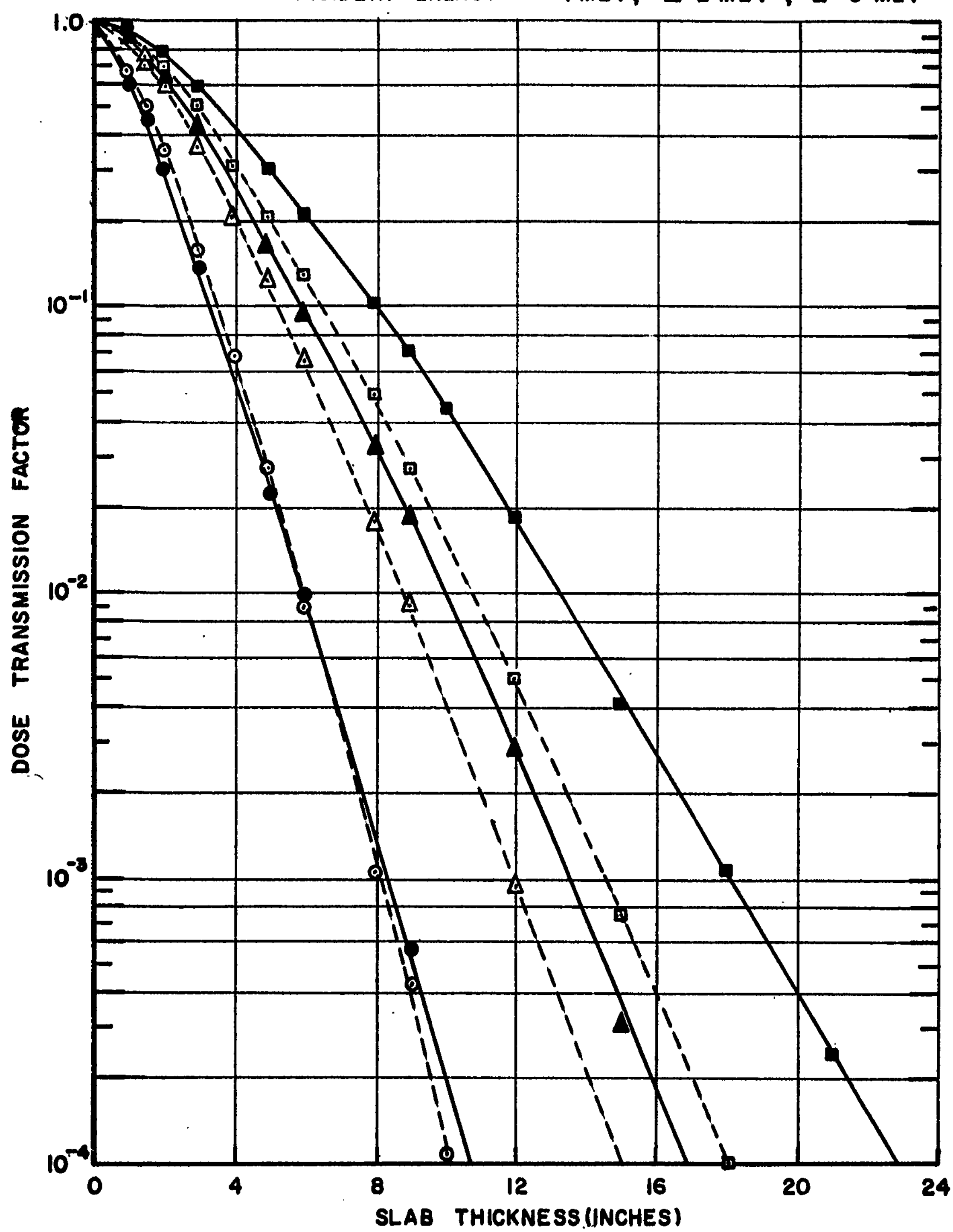


FIG. 43 (cont'd) NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND INCIDENT ENERGY

INCIDENT ANGLE — 0°

SLAB MATERIALS — WATER - INDICATED BY SOLID SYMBOLS & SOLID LINES; BORATED POLYETHYLENE (8 % B_4C BY WEIGHT) - INDICATED BY HOLLOW SYMBOLS & DASHED LINES

INCIDENT ENERGY — ● 1 MEV ; ▲ 2 MEV ; ■ 3 MEV

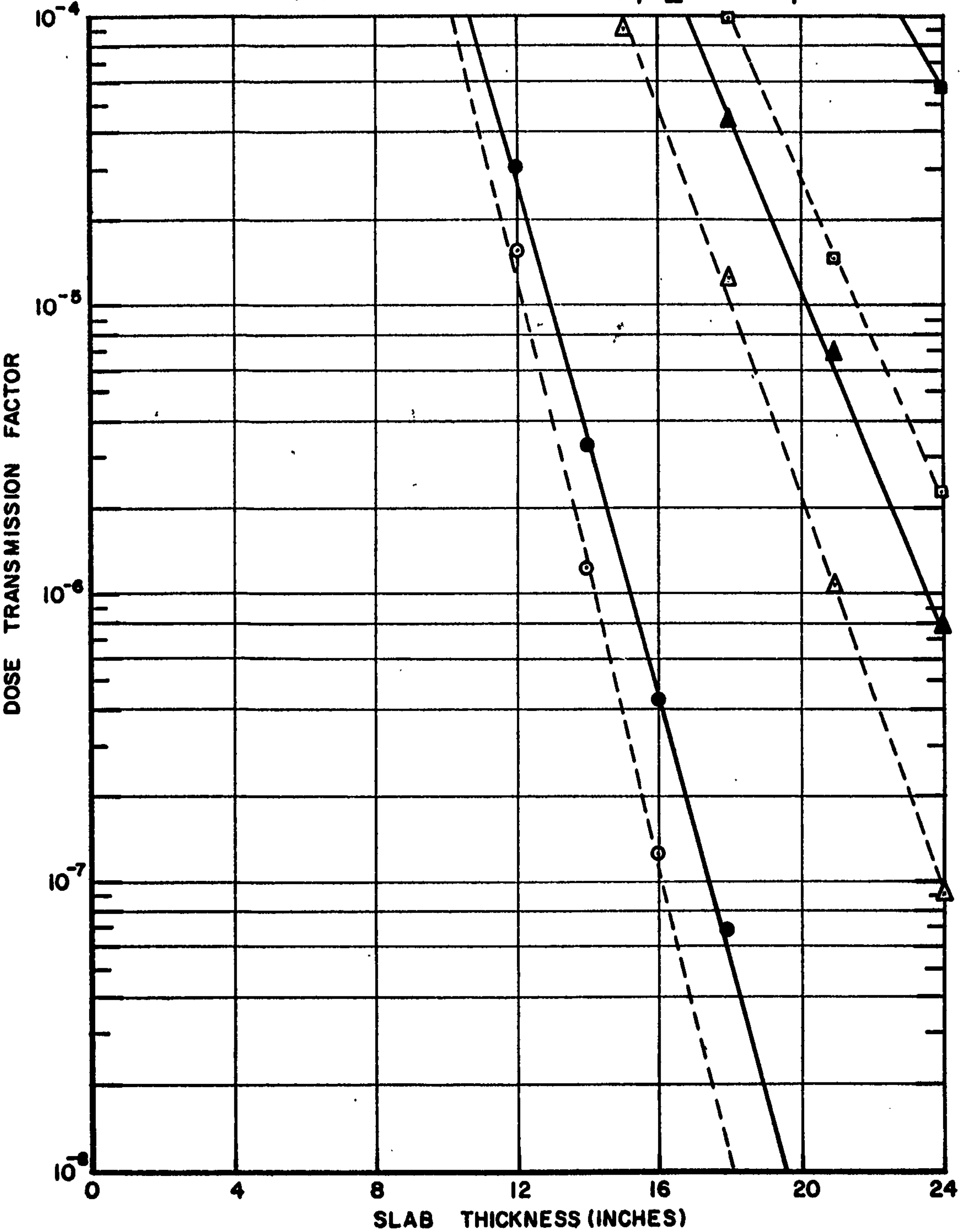
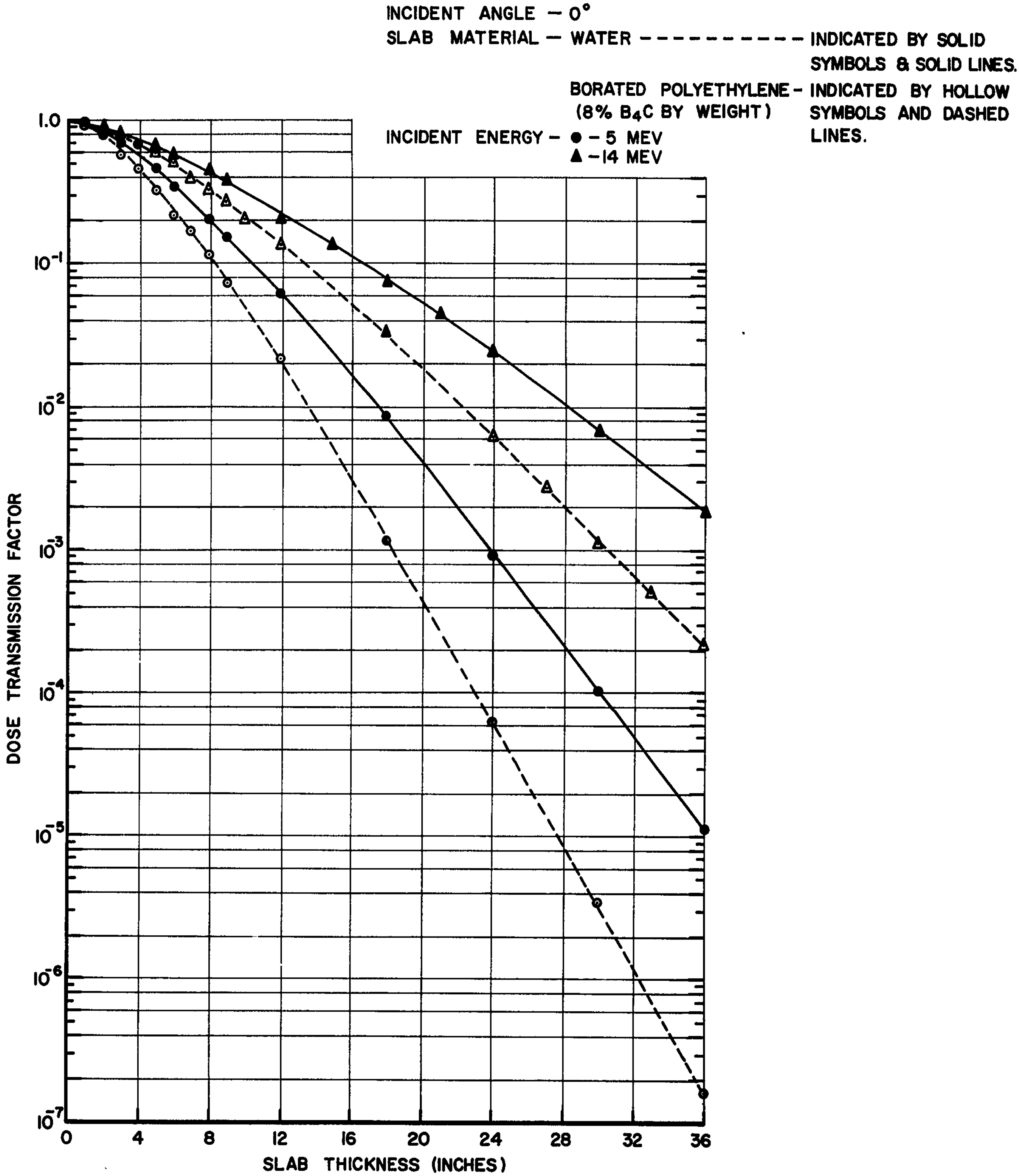


FIG. 44 NEUTRON DOSE TRANSMISSION AS A FUNCTION OF SLAB THICKNESS AND INCIDENT ENERGY



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